PugetSoundScienceUpdate

Draft April 12, 2011

PugetSoundPartnership
our sound, our community, our chance

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Editor’s note

The Puget Sound Science Update is a represents the state-of-the-science supporting the work of the Puget Sound Partnership to restore and protect the Puget Sound ecosystem. The Puget Sound Science Update represents an advancement in the development and use of science to support Puget Sound recovery in two important ways. First, the content of the Puget Sound Science Update was developed following a process modeled after the rigorous peer-review process used by the Intergovernmental Panel on Climate Change (IPCC), in which small author groups produced draft assessment reports synthesizing existing, peer-reviewed scientific information on specific topics identified by policy leaders. These drafts were peer-reviewed before the final reports were posted. Second, the Puget Sound Science Update will be published on-line following a collaborative model, in which further refinements and expansion occur via a moderated dialog using peer-reviewed information. Content eligible for inclusion must be peer-reviewed according to guidelines.

In the future, there will be two versions of the Update available at any time:

(1) a time-stamped document representing the latest peer-reviewed content (new time-stamped versions are likely to be posted every 4-6 months, depending on the rate at which new information is added); and

(2) a live, web-based version that is actively being revised and updated by users.

The initial Update you see here is a starting point to what we envision as an on-going process to synthesize scientific information about the lands, waters, and human social systems within the Puget Sound basin. As the document matures, it will become a comprehensive reporting and analysis of science related to the ecosystem-scale protection and restoration of Puget Sound. The Puget Sound Partnership has committed to using it as their ‘one stop shopping’ for scientific information—thus, it will be a key to ensuring that credible science is used transparently to guide strategic policy decisions.

The Update is comprised of four chapters, and you will note that some are still at earlier stages of completion than others. Over time—through the process of commissioned writing and user input through the web-based system—the content of all four chapters will be more deeply developed. We are relying in part on the scientific community to help ensure that the quality and nature of the scientific information contained in the Update meets the highest scientific standards.

Preface

Who are the authors of the Puget Sound Science Update?

Leading scientists formed teams to author individual chapters of the Puget Sound Science Update. These teams were selected by the Puget Sound Partnerhship's Science Panel in response to a request for proposals in mid-2009. Chapter authors are identified on the first page of each chapter. Please credit the chapter authors in citing the Puget Sound Science Update.

What are the Puget Sound Partnership and the Science Panel?

Please visit psp.wa.gov to learn about The Puget Sound Partnership.

Please visit science panel web page to learn about the Science Panel.

Has the Puget Sound Science Update been peer reviewed?

The original chapters of the Puget Sound Science Update were subjected to an anonymous peer review refereed by members of the Puget Sound Partnership's Science Panel. Reviewers are known only to referees on the Science Panel and the Partnership's science advisor.

What is "content pending review"?

The future web presentation is intended to offer a venue for updating, improving, and refining the material presented in the Puget Sound Science Update. Suggested amendments and additions are presented as "content pending review" on each page when an editor, perhaps working with a collaborating author, has developed some new content that has not yet been formally adopted for incorporation into the section. As "content pending review," this content should not be cited or should be cited in a way that makes clear that it is still in preparation.

How can I contribute new material to the Puget Sound Science Update?

Please visit the Puget Sound Partnership website to learn about how you can help improve, update, and refine the Puget Sound Science Update, or send an e-mail to pssu@psp.wa.gov to get the process started.

How can I cite the Puget Sound Science Update?

We recommend citations this version in the following format:

[Authors of specific chapter or section]. April 2011. [Section or chapter title] **in** Puget Sound Science Update, *April 2011* version. Accessed from http://www.psp.wa.gov/. Puget Sound Partnership. Tacoma, Washington.

"Content pending review" of the Puget Sound Science Update has not been fully reviewed for publication. If you elect to cite this information, we recommend that you contact the named author(s) to cite as a personal communication or cite the web-presentation using the following format:

[Authors of pending material]. In prep. Content pending review presented in *[Section or chapter title]* **in** Puget Sound Science Update. Accessed from http://www.psp.wa.gov/. Puget Sound Partnership. Tacoma, Washington.

Chapter 1A. Understanding Future and Desired System States

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Introduction

The Puget Sound Partnership (PSP) is charged with the task of reversing the decline in the ecological condition of Puget Sound and restoring its health by 2020 [1]. Since the creation of the PSP and the publication of the Puget Sound Partnership Action Agenda, the Puget Sound ecosystem has become a national example of implementation of ecosystem-based management (EBM; [2]). As the Puget Sound region considers the dozens of near-term actions for ecosystem recovery, policy makers, resource managers, and scientists must be able to answer two key questions about the state of the ecosystem: 1) where are we going?, and 2) how do we know when we get there? Answering the question of what constitutes a healthy Puget Sound requires a thoughtful articulation of what the future of Puget Sound should be and scientifically rigorous means for measuring progress towards this desired future. This is the aim of this chapter.

Terminology and Concepts **Open Standards**	Open Standards for the Practice of Conservation , a set of adaptive management steps developed by the Conservation Measures Partnership as a framework for planning and implementing conservation action. The Open Standards methodology is being used by the PSP to put the Action Agenda into a performance management framework.
Results Chain	One component in the Open Standards framework being used by the PSP. A tool showing how a particular action taken will lead to some desired result. Diagrams link short-, medium- and long-term results in "if... then" statements. The three basic elements are a strategy, expected outcomes, and desired impact.
Management Strategy Evaluation	(MSE) Conceptual framework that enables the testing and comparison of different management strategies designed to achieve specified management goals
Performance Management	A system to track implementation and communicate progress of a conservation project or program

For more information and links to references, see Glossary

A properly designed monitoring program is essential for determining progress towards a desired future ecosystem state. Monitoring encompasses the routine measurement of ecosystem indicators to assess the status and trends of ecosystem structure and function. Successful monitoring requires consideration what we should monitor and why we are monitoring it. Broadly, there are two goals for monitoring in the Puget Sound ecosystem. The first goal is to monitor status and trends of the ecosystem. This may take the form of snapshots of specific regions, or, more usefully, status monitoring tracks variability in carefully selected indicators over time. Status monitoring is fundamentally concerned with documenting spatial and temporal variability in ecosystem components and thus ideally relies on consistent long-term monitoring in a network of sites.

A second aim of monitoring is to evaluate the effectiveness of management strategies. Effectiveness monitoring thus aims to detect changes in ecosystem status that are caused by specific management actions. Effectiveness monitoring is ideally informed by a conceptual or numerical system model. Such models can be used to generate predictions or hypotheses of how management actions might shift the system towards a desired state. A carefully crafted plan for effectiveness monitoring requires indictors of 1) compliance with regulations; 2) ecosystem pressures (the object of management action); and, 3) status of the ecosystem affected by these pressures. Such a plan for effectiveness monitoring allows a determination of how well predictions about appropriate management strategies performed, and provides a formal means for learning about the system and how management actions influence the system.

In the 2008 Action Agenda, the PSP established five priority strategies, one of which includes developing a performance management system to track and assess progress towards an ecologically healthy Puget Sound [1]. To this end, the PSP has adopted the Open Standards for the Practice of Conservation ("Open Standards"[3]) as a framework for implementing and tracking the progress of the Action Agenda. The Open Standards describe steps in the design, implementation and monitoring of conservation projects, two components of which are the identification of ecosystem components and indicators for those components; and development of "Results Chains," diagrams that map specific management strategies to their expected outcome (e.g., reduction of a threat) and their impact on key components of the ecosystem using a series of "if...then" statements [4]. The Open Standards is thus a tool that can be used to articulate "where we want to go", and inform both status and effectiveness monitoring to determine if we reached our goal.

In this section of the Puget Sound Science Update (PSSU), we first critically review published reports that describe desired future states of the Puget Sound ecosystem, and suggest ways to incorporate new information generated by such future visions into the results chain model. We next introduce a flexible framework for selecting indicators of the biophysical components of the ecosystem (the human components are addressed in Section 1B of this document, 'Incorporating Human Well-Being into Ecosystem-Based Management'), and establish transparent criteria for judging an indicator's ability to reliably track changes in ecosystem status. Using these criteria, we then provide an evaluation of 270 candidate ecosystem indicators. Finally, we review targets and benchmarks for ecosystem indicators in Puget Sound; where they are found wanting, we describe a number of approaches that could be applied to scientifically inform the development of management targets and benchmarks. It should be noted here that while the PSP and the authors of this document consider the Puget Sound ecosystem to be inclusive of humans, this section develops indicators for the biophysical components of the ecosystem, and therefore in those sections, the term "ecosystem" refers exclusively to the biophysical components.

Ecosystem Health

Rapport and colleagues (1985) suggested that the responses of stressed ecosystems were analogous to the behavior of individual organisms [5]. Just as the task of a physician is to assess and maintain the health of an individual, resource managers are charged with assessing and, when necessary, restoring ecosystem health. This analogy is rooted in the organismic theory of ecology advocated by Clements over 100 years ago, and is centered on the notion that ecosystems are homoeostatic and stable, with unique equilibria [6]. In reality however, disturbances, catastrophes, and large-scale abiotic forcing create situations where ecosystems are seldom near equilibrium. Indeed, ecosystems are not “superorganisms”—they are open and dynamic with loosely defined assemblages of species [7]. Consequently, simplistic analogies to human health break down in the face of the complexities of the non-equilibrial dynamics of many ecological systems [8]. Even so, the phrase “ecosystem health” has become part of the lexicon of EBM and resonates with stakeholders and the general public [8]. And, “ecosystem health” is peppered throughout the PSP Action Agenda. Thus, while we acknowledge the flaws and limitations of the phrase, we use it here because it is a familiar phrase that is salient in the policy arena.

The Future of Puget Sound: Where are We Going?

The charge is clear: restore the ecological health of Puget Sound by 2020. What is less clear, however, is what future the citizens of the Puget Sound region desire. Understanding what future we want, and what futures are possible, is critical to informing management decisions about complex systems such as Puget Sound, comprised of multiple unpredictable components. The theme of any individual vision of the future may range from particular ecosystem states (e.g., healthy orca populations, clean water) to socio-economic conditions (e.g., thriving ports, efficient and integrated public transportation). However, comprehensive visions of future states require that Puget Sound be considered in the context of a coupled social-ecological system, with the socio-economic system influencing the ecological system, and vice-versa. All components of this complex system are in turn being transformed by driving forces that can be either internal or external to the system. These unpredictable and largely uncontrollable driving forces, for example, climate change, the national and global economies, human desires, behavior and attitudes, each have their own potential trajectories that will help shape the future state of the Puget Sound ecosystem. For example, whether the future climate of Puget Sound is warmer and wetter, or warmer and drier, will certainly shape management strategies aimed at protecting species that use the freshwater streams and rivers in Puget Sound, such as salmon. Describing the future state of Puget Sound, therefore, goes beyond making predictions based on past observed trends in the ecological system and identifying actions that Puget Sound resource managers can implement. Understanding the myriad potential futures of Puget Sound is critical to setting targets aimed at achieving goals for restoring the health of Puget Sound by 2020.

This section will review previous efforts to describe alternate futures for Puget Sound, highlight the trade-offs inherent in these scenarios, particularly in light of drivers generated outside of the Puget Sound ecosystem, and draw connections between future scenarios and management strategies, including the importance of setting targets and deriving quantitative measures of progress. Finally, we suggest directions for continued efforts to describe alternate futures of Puget Sound.

1. Future States of Puget Sound

Describing the future state of Puget Sound has been approached in several ways, including using a formal scenario planning process, within the context of a regional planning strategy, using models and GIS (Geographical Information System) tools to map potential changes on the landscape, and setting specific targets for the desired future ecological system. Most of the work has been focused on the nearshore habitats of Puget Sound, with limited consideration of other domains of the ecosystem (e.g., rivers, forests, freshwater wetlands). Each approach described here is one component of what we see as a comprehensive future scenario process, beginning with a declaration of priorities by policy makers, followed by a thorough exploration of the driving forces behind the Puget Sound ecosystem and their potential trajectories, and finally, drawing explicit links (mediated by the driving forces) between potential policy decisions, biophysical states, and their consequences for the ecological system and ecosystem goals. As yet, there is no single “soup-to-nuts” approach to describing a future Puget Sound, though some of the efforts reviewed below are still works in progress.

Puget Sound Regional Council's Vision 2040

The Puget Sound Regional Council's "Vision 2040," adopted in 2008 and amended in 2009, is essentially a declaration of priorities for the future of Puget Sound by the major policymakers and politicians in the Central Puget Sound region [9]. Vision 2040 describes the growth management, environmental, economic and transportation strategies for the region. It co-prioritizes people, the economy, and the environment, and lists a series of goals and future actions, some of which are supported by existing policy. The document charts a pathway for land development and design, referencing existing land-use development policy (Washington State Growth Management Act) and establishes goals for matching development patterns with human well-being. Regional economic prosperity is a goal to be achieved by implementing a separately-established Regional Economic Strategy [10]. Finally, a multimodal regional transportation system is a priority, "integrating freight, ferries, highways, local roads, transit, bicycling and walking" [9].

Vision 2040 provides a framework within which regional planning on land use, economic development, and transportation can occur. The strategy explicitly takes into consideration the connectedness of regional planning and the environment. The document outlines goals, actions and implementation strategies for transportation and development, primarily from a policy and planning perspective. The drivers of the ecosystem are policies, which alter the (terrestrial) landscape according to a broad set of guidelines aimed at encouraging density within urban areas and limiting development outside of urban areas, and strengthening public transit and non-motorized transportation without compromising regional economic growth. There is a single vision of an ideal future Puget Sound region, and this document lays the groundwork for achieving that vision.

Summary: Within the context of a comprehensive effort to describe potential futures of Puget Sound, Vision 2040 serves as a statement by the citizens, as represented by their elected officials. Missing from this are more specific statements from the public about their views on, for example, a healthy Puget Sound. However, to date, no comprehensive survey or collection of citizen opinions about the future of Puget Sound exists, and therefore this document is the best proxy we have for gauging broad societal goals and desires. Any description of potential Puget Sound futures should include the public's desires as assurance that the ecosystem is headed in a direction supported by the public, and therefore this document is useful as one piece in the future scenario process.

Puget Sound Nearshore Partnership and University of Washington Urban Ecology Research Lab, "Future Scenarios

In another approach to describing a future Puget Sound, the Puget Sound Nearshore Partnership and the Urban Ecology Research Lab (UERL) produced "Future Scenarios" [11], which employs a formal scenario-building process to identify the driving forces of change in the Puget Sound ecosystem, and to develop multiple alternative scenarios based on the uncertainty in and interactions between those driving forces. Scenario building is a systematic method that has been applied to coupled social-ecological systems by, for example, the Millennium Ecosystem Assessment [12], and aims to generate more flexible approaches to EBM through the incorporation of uncertainty and multiple knowledge types. The fundamental premise is that the future is unknown, and that it is a function of several key factors that interact to create multiple potential future outcomes.

Through a series of visioning exercises with stakeholders and experts on the Puget Sound social-ecological system, two "key" drivers (climate and human behavior/perceptions) and nine "supporting" drivers (demography, development patterns, economy, governance, knowledge/information, natural hazards, public health, and technology/infrastructure) were identified, as were the interactions among them. The "key" drivers represent the most important and uncertain driving forces relevant to the issue, in this case the nearshore ecosystem of Puget Sound. Based on the potential trajectories of the key drivers and their interactions with the supporting drivers, six scenarios were developed. Narratives of each scenario described the prosperity, human attitudes, climate regime, development patterns, governance structure and demographics of a future Puget Sound, primarily as a function of the key drivers, climate and human behavior/perceptions and without drawing explicit links to component of the ecological system. Each narrative was rooted in a storyline, described by society's worldview, human-nature relationships, and future outlooks (i.e. optimistic vs. pessimistic, or positive about human-nature relationships vs. hostile towards the environment).

The six scenarios spanned a broad range of social and climatic conditions, coupled with resulting effects on the ecological system. For example, in the "Collapse" scenario, climate change manifested as drier and warmer conditions in Puget Sound, and human behavior was self-interested and focused on the near-term. High levels of resource extraction and pollution caused harm to ecosystem function. Poor economic performance and increasing government expenditures led to fewer investments in infrastructure and public services, and eventual out-migration of the population. On the other end of the spectrum, the "Forward" scenario described a future with only limited climate change in Puget Sound and a cooperative social ethic, leading to a proactive approach to environmental issues and higher quality of life. There was increased population and economic growth. There was a greater understanding of the linkages between society and nature, leading to a stronger relationship between residents and their environment.

Summary: "Future Scenarios" gives a very thorough treatment to the socio-eco-political matrix within which the nearshore ecosystem (to which this analysis was limited) exists. Links are drawn between attitudes, economics, politics and climate, and alternative trajectories are explored for each--an important acknowledgment that there is great uncertainty involved in any vision of the future. This approach to fleshing out ecosystem drivers and their trajectories is critical in a comprehensive effort to describe the future of complex social-ecological systems like Puget Sound. The next step of this project is to explicitly link the drivers and scenarios to the ecological constituents and interactions.

Future Risk Assessment Project (FRAP) and Ecosystem Portfolio Model (EPM)

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) has developed several future scenarios of Puget Sound by coupling the Future Risk Assessment Project (FRAP), the creation of one set of land-use scenarios, with the Puget Sound Ecosystem Portfolio Model (EPM; [13]), a suite of models that evaluate the effects of land-use scenarios on nearshore ecosystems. The Puget Sound Nearshore Science Team and scientists from Oregon State University generated land-use scenarios based on three potential directions for land-use policy: status quo, where current trends continue forward; managed growth, which incorporates aggressive policies directing growth into urban areas; and unconstrained growth, which relaxes land-use regulation. Each scenario modulates several parameters governed by growth policy: population distribution, urban and rural development patterns, nearshore development pattern/intensity, and protection of open space. These scenarios were input to a GIS model, generating terrestrial maps of land use/land cover for Puget Sound [14].

The EPM models link land-use patterns generated by policy scenarios to ecosystem state, and therefore analyses can be directed towards specific goals. One such set of links was developed targeting human well-being, one of the six major goals of the Puget Sound Partnership. Using a list of human well-being indicators chosen in consultation with multiple expert groups, explicit connections are drawn between land-use patterns and metrics of human well-being using existing data and models. For example, each land-use scenario developed by FRAP results in some degree of shoreline modification, which is then linked to indicators of human well-being, one example of which is recreational beach use. A statistical model predicts the effects of land-use development on recreational beach use as a function of recreational visit data, demand (based on population density) and access (based on travel cost), each of which is affected by shoreline development.

Summary: The FRAP/EPM approach emphasizes connections between patterns on the landscape, generated through simple policy-driven scenarios, and specific ecosystem states that can be linked to a broader ecosystem or policy goal, in this case human well-being. In the context of a comprehensive future scenario process, this is a critical step that highlights the consequences of individual policy decisions, like land-use development, for ecosystem goals, in this case human well-being. This technique could also be used in conjunction with scenarios that generate ranges of responses by the social-ecological system. For example, to these same land-use policy scenarios could added climate change scenarios that will alter the way the ecological system responses to, for example, shoreline modification. Under warmer, wetter conditions, erosion patterns and the absolute amount of shoreline in Puget Sound may change, both of which will affect recreational beach use. This tool linking changes made on the landscape to ecosystem goals is helpful in charting a path towards ecosystem goals and in predicting the feedbacks of policy decisions.

Puget Sound Salmon Recovery Plan

The Puget Sound Salmon Recovery Plan, in contrast to the above approaches, uses specific targets to describe the future, by establishing regional and watershed-specific abundance and productivity targets for threatened Pacific salmon and bull trout populations. In 1999, Puget Sound Chinook Salmon, Coastal/Puget Sound bull trout and Hood Canal summer chum were listed as threatened under the Endangered Species Act (ESA). Subsequently, a number of independent recovery plans for Puget Sound salmon populations were initiated, and the Puget Sound Salmon Recovery Plan aimed to combine the efforts and strategies of several groups, most notably the Shared Strategy for Puget Sound (Shared Strategy) and NOAA’s National Marine Fisheries Service [15]. The Shared Strategy generates individual watershed targets for salmon populations based on technical models and historic information, setting target ranges for salmon abundance and productivity.

Using these watershed-specific targets, the Salmon Recovery Plan then establishes short- and long-term numerical goals, identifies limiting factors, and offers specific strategies, in some cases at the scale of individual tributaries, for reaching those goals. For example, the Lake Washington/Cedar River/Lake Sammamish Chinook salmon population's 10-year goal is 1,600 spawners, and the long-term goal is between 2,000-12,000 spawners, allocated among the different water bodies. The major limitations to achieving increases in productivity and abundance include altered hydrology, loss of riparian vegetation, lack of woody debris, and high temperatures and pollution levels. The strategies identified to achieve the abundance and productivity goals include protecting and managing upper watersheds, restoring stream habitat, improving lake habitat and reducing the impacts of urban development. Individual actions are recommended for specific tributaries or water bodies.

The Shared Salmon Recovery Plan defines the future in terms of specific targets for the ecological system (salmon abundance and productivity), identifies threats to achieving those targets, and lays out strategies and actions for addressing the threats. While it does not offer alternate future scenarios, it outlines an adaptive management approach to investigate and incorporate sources of uncertainty such as climate change, interactions between wild and hatchery fish, effects of poor freshwater and marine water quality, and nearshore habitat processes.

Summary: This approach is one of few that specifically identifies targets for Puget Sound ecosystem goals. In the context of a complete results chain approach to achieving a healthy Puget Sound, setting targets is critical for understanding the trade-offs between different goals (see below). In the context of a comprehensive future scenario process for Puget Sound, targets represent concrete objectives against which results from statistical models (e.g., EPM) and potential future states of driving forces can be compared. For example, under a warmer, wetter climate, with a population focused on near-term objectives, a flat local economy and status-quo land use policies, can the stated salmon productivity targets be reached for each watershed? Under which scenarios are the targets achievable? Asking these complex questions highlights the need for a comprehensive effort to describe the future Puget Sound.

Summary of Future Scenario Efforts

The above review of four very distinct efforts to describe a future Puget Sound highlights what is needed, and what is missing, in a comprehensive future scenario process. Comprehensive visions of a future Puget Sound will chronicle the political motivation and citizens' desired state; explore the uncertainty in the driving forces of the social-ecological system, including climate change; draw explicit links between the drivers and the ecological state; and develop targets for future state characteristics based on existing data and models. "Vision 2040" provides the best measure we have of the public's vision for the future of Puget Sound; however, this description is missing specific references to the ecological system which could help management predict the public's response to or support for certain decisions or trade-offs. Characterizing the major uncertainties in the system and offering potential future scenarios based on these is a crucial step in adequately matching ecosystem goals with strategies and actions, and "Future Scenarios" is a very thorough treatment of the driving forces behind this uncertainty. Any thorough approach to describing potential futures must incorporate climate scenarios, as well as the key socio-economic drivers in the system. If these driving forces can be incorporated into the model-based scenarios and on-the-ground biophysical depictions of policy decisions (effectively exemplified by FRAP and EPM), then more accurate assessments of alternate management strategies will be possible. This is a formidable task, and the work reviewed above contributes towards that end. A thorough effort to describe a future Puget Sound (i.e., Where are we going?) is a partner to larger effort in this document, developing indicators for the system (Are we there yet?).

Key point: Characterizing the major uncertainties in the system and offering potential future scenarios based on these is a crucial step in adequately matching ecosystem goals with strategies and actions. Any thorough approach to describing potential futures must incorporate climate scenarios, as well as the key socio-economic drivers in the system.

Trade-offs and Targets

Among other marine ecosystem management programs in North America, the most common approach to defining the future is akin to the FRAP/EPM method described above: develop predictions for future ecological states based on existing information, and specifically, generate a few land-use scenarios based on policy decisions governing development, growth management, pollution controls, transportation and/or conservation, and connect the resulting landscape patterns to ecological function, such as nutrient or sediment inputs (e.g. [16, 17]). Less common is a thorough examination of the socioeconomic and climate drivers of ecosystem dynamics, as in the UERL/PSNERP "Future Scenarios." However, even in cases where the drivers of the ecosystem are well described and incorporated into future scenarios, their utility is limited by the extent to which linkages are drawn between drivers, ecological state, and goals or targets.

Most future scenario-building efforts (including several reviewed above), lack an explicit treatment of the trade-offs required to successfully arrive at a desired future state. Moving from citizen desires to ecosystem reality requires confronting trade-offs among multiple goals. For example, the U.S. Government's roadmap for restoring the Louisiana-Mississippi Coast Ecosystem acknowledges that stakeholders must "jointly evaluate trade-offs that will likely be necessary" to meet the multiple goals of ecosystem function, resilience, economics and climate adaptation [18]. Such trade-offs are cast in sharp relief when considering the tension between local economic prosperity, the global economy and water quality in Puget Sound. The Ports of Seattle and Tacoma together comprise the third busiest container port in the U.S. [19], and a large proportion of the Puget Sound regional economy relies on the import and export of goods through the ports. A growing demand for imports and exports through Puget Sound ports, generated by a flourishing global economy, could increase shipping traffic. The Ports of Seattle and Tacoma are already challenged to meet port productivity goals as well as water quality requirements, and a rise in traffic through the Ports would exacerbate that particular challenge, if not necessitate additional construction along Puget Sound shorelines. Both increased shipping traffic and increased hardening of shorelines negatively impact Puget Sound marine species, food webs, habitat, water quality – each a PSP goal. Other trade-offs likely to emerge include those between population increase, development pressures and habitat protection; population increase, agricultural demands and minimum stream flows; and economic prosperity, shipping traffic and invasive species control. As these examples highlight, achieving human well-being and ecological function without sacrificing economic prosperity in Puget Sound will require some compromises.

In some cases, thorough consideration of trade-offs is not possible owing to the absence of targets--the desired future numeric value for an ecosystem indicator. In large part, quantifiable targets related to the state of the Puget Sound ecosystem are missing from future scenario efforts (one major exception to this is the Shared Salmon Recovery Plan). In the absence of targets, the assessment of progress and a complete understanding of trade-offs are elusive. Establishing targets forces confrontation with trade-offs; without targets, the definition of "success" – and the route to get there – is flexible. Furthermore, in the context of a future scenario process, evaluation of scenarios is hampered without targets. Full evaluation of trade-offs, in turn, involves describing the human drivers of ecosystem change, such as behavior and perception, which highlights the importance of including these driving forces in future scenario processes.

Key point: Establishing ecosystem targets is essential as it forces confrontation with trade-offs among targets. Full evaluation of trade-offs requires examination of the human drivers and these driving forces should be central in future scenario processes.

Management Strategy Evaluation

One means of addressing trade-offs and targets is management strategy evaluation (MSE), a conceptual framework that facilitates testing and comparison of different management strategies designed to achieve specified management goals [20]. The MSE process is analogous in many ways to the approach employed by the FRAP/EPM effort described previously. Born from the concepts of adaptive management of resources [21] and management procedure evaluation [22], MSE is an analytical process that follows six basic steps:

- Policy objectives, target values, and performance measures (measures of success) for important resources are defined and quantified.
- A management strategy is designed to achieve the objectives.
- The strategy is implemented in an operating model that simulates ecosystem processes relevant to the resources of interest. The model may be simple or complex, depending on the underlying questions.
- A simulated monitoring program draws imperfect data from the operating model.
- An assessment model is run to determine the effect of management on indicator variables measured by the simulated monitoring program. The levels of the indicators are compared to the pre-determined target values; the difference is a measure of performance.
- Depending on the outcome of the assessment, decision rules will be activated that either continue or adjust the management strategy, until the objective is met.

This process is repeated for multiple management strategy alternatives, which allows comparison of different strategies—in terms of both successes (positive performance measures; rapid progress) and weaknesses (negative performance measures, slow progress)—in attaining desirable future states. In this way, the potential effectiveness and the potential trade-offs of the strategies are understood.

Several operating models that are available or in development could support MSE of alternate Puget Sound futures. Some available models focus on aquatic and marine issues such as municipal water supply [23] and the relationship between terrestrial activities and marine biogeochemistry (e.g., [24]). Others focus on terrestrial issues such as land use and urbanization impacts on species diversity [25]. Several models in development simulate the structure of the marine food web (e.g., the Ecopath with Ecosim model of Central Puget Sound [26]), and are well-suited to forecast trade-offs between different resources or stakeholders as a result of simulated management actions. Continued development of such models is a high priority.

Key Point: Formal Management Strategy Evaluation (MSE) is an important tool for assessing management scenarios. Several computer models are available that could support MSE, but continued model development should be a high priority.

An Expanded Results Chain Model

Future scenarios are a critical tool for informing and refining conservation strategies. The PSP has adopted the Open Standards for Practice of Conservation framework for performance management. A key component of the Open Standards is “results chains,” which map management strategies to their expected outcome (e.g., reduction of a threat) and their impact on key components of the ecosystem (Figure 1). An individual results chain is comprised of multiple components: a goal is linked to a strategy, such as a policy decision, for achieving that goal; associated with each strategy are one or more outcomes of that strategy; a second outcome or set of outcomes describes an expected change in the ecosystem threat; the threat outcome is linked to an ecological impact, which relates to the goal (Figure 1). In the context of the Open Standards, alternate future scenarios, whether describing possible trajectories of external drivers (e.g., climate change, human attitudes), policy outcomes (e.g., Shoreline Management Act amendments), or the state of the economy, can be incorporated into results chains by generating ranges for outcomes or impacts, rather than single values. In this way, alternate futures help set realistic targets for desired ecological states.

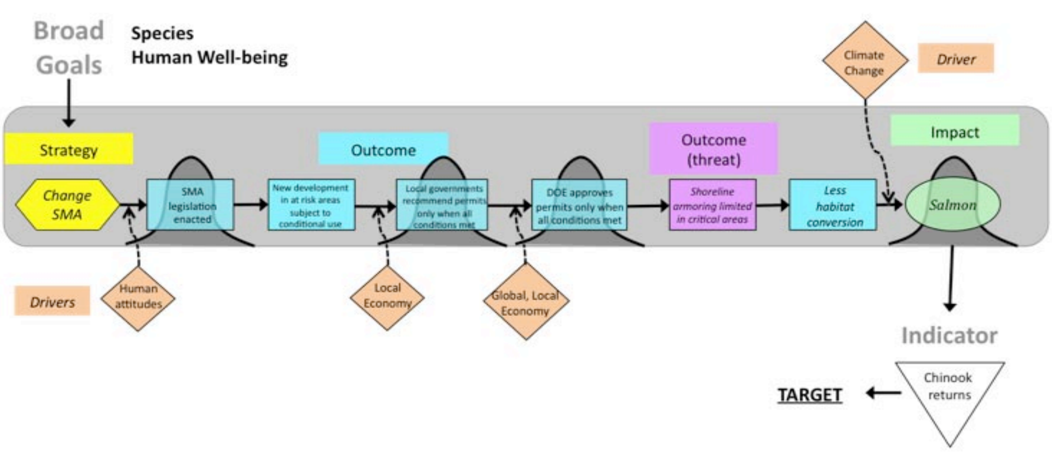


Figure 1. An example of a modified results chain, incorporating the influence of future scenarios of drivers (orange diamonds) on links in the chain, adding an example of an indicator (blue triangle) and showing where a target would be included. The effect of future scenarios on a results chain is shown here by overlaying a distribution of possible conditions (grey curves) for outcomes or impacts where they are potentially influences by future conditions of external drivers. Original chain from [4].

To illustrate the utility of future scenarios in the results chain framework, we use an example where a set of land protection actions from the Puget Sound Partnership's Action Agenda is aggregated into a results chain describing regulatory strategies for protecting and enhancing ecosystem components. One sub-chain focuses on a strategy to amend the Shoreline Management Act (SMA) by requiring conditional use permits for land development (Figure 1), with the ultimate objective of converting less habitat, which would positively impact many components of the ecosystem, including salmon [4]. The first "if...then" step in this sub-chain is that if the SMA is amended, then the revised version will be enacted. This initial step requires approval by voters, through their elected legislative representatives, and is therefore subject to the influence of human attitudes and perceptions. Surveys of Puget Sound citizens and stakeholders have indicated that, in general, people do not think Puget Sound is alarmingly unhealthy, and they are disinclined to make major sacrifices to protect and restore the ecosystem [27]. Therefore, there is some uncertainty, a function of human attitudes, about whether this legislation would be approved, and that uncertainty is described by a range of potential policy outcomes, rather than a single deterministic outcome. In addition, assuming all the outcomes in the results chain are achieved, and less habitat is converted by development, climate change can still influence the abundance and productivity of salmon populations through other mechanisms, and the impact of regulation changes on salmon will be mediated by the potential influence of climate change. Therefore, the goal "Salmon" is represented as a range of possible salmon populations, rather than a single value. This example illustrates the role of future scenarios in developing performance measures and outcomes for conservation plans.

We have also modified the results chain by adding in indicators, which are connected to the Impact (Goal) – in this case, the indicator of "Salmon" is "Chinook returns." Associated with each indicator, also, would be a target, in this case, likely watershed-specific targets for Chinook salmon returns, such as those generated by the Shared Salmon Strategy.

"The future ain't what it used to be." Y. Berra

Our review of the few efforts to envision a future Puget Sound suggests considerable room for future work. While there is clear agreement that the future state of Puget Sound should be different than it is now, the region lacks a lucid vision of the desired state of the coupled human-ecological system. The strong links between human activities and nearshore ecosystem components have resulted in most of the effort being direct towards this domain; however, there is no doubt that future scenarios for the whole of Puget Sound - from "sea to summit"- are required. Externalities of human and natural origin are important driving forces in this coupled system and should be included in analyses of scenarios. And, ultimately, these scenarios are most useful if they identify trade-offs and develop means for operating along the axes between trade-offs. The lack of management targets for most components of the Puget Sound ecosystem allows managers and policy makers to avoid confronting many trade-offs and thus encourages somewhat narrow (e.g., single ecosystem domains) or vague and ill-defined visions of the future. However, our review reveals that the foundation to generate scenarios of a future Puget Sound is in place. As the efforts described here continue and expand and new endeavors begin, we expect more comprehensive visions of Puget Sound's possible future to emerge.

Key point: While there is clear agreement that the future state of Puget Sound should be different than it is now, the region lacks a lucid vision of the desired state of the coupled human-ecological system. However, the foundation to generate scenarios of a future Puget Sound is in place. As the efforts described here continue and expand, we expect more comprehensive visions of Puget Sound's possible future to emerge.

Table 1. Summary of final scenarios generated by "Future Scenarios"; adapted from Table 6.1 in [11].

Forward: Low climate change coupled with a greater social ethic of cooperation provided the Puget Sound the opportunity and resources to proactively address environmental problems and improve the quality of life for all of its residents. While the region's economy continued to grow and immigration doubled the Sound's population, the region managed to maintain and restore ecological function. Residents, governments and industry shared a new understanding of the Puget Sound ecosystem as an integrated human-ecological system creating a renewed relationship with their environment.
Order: While climate change was a best-case scenario, population growth coupled with increasing consumption placed pressure on the Puget Sound's resources. An increasingly fragmented governmental structure spurred conflict between municipalities and interest groups. In spite of existing environmental regulations, a lack of coordination among governmental agencies was a major obstacle in improving ecosystem function. Sprawling developments coupled with a low investment in the region's infrastructure, education and health significantly reduced the quality of life in the region.
Innovation: More and greater climate fluctuations increased the Puget Sound's vulnerability to floods, windstorms and fires. Technological innovation mitigated negative impacts on residents and infrastructure. The high tech industry led the regional economy, drawing in skilled labor and high wages and largely controlling the political arena. Growth rates of new ideas, production, immigration and housing development all increased, generating wealth and jobs. Innovation allowed per capita consumption levels to remain high through increased efficiency and closed-loop industrial processes.
Barriers: Society in the Puget Sound region divided as the disparity between the rich and poor was magnified. Escalating climate impacts posed significant threats to private property, regional infrastructure and natural resources. Residents responded by building stronger walls, moving uphill and securing their investments. As cost of fuel and mitigation rose, the rich buffered their families from impeding harm, while the poor were left behind with a continuously degrading economy. Government regulations were relaxed in an effort to overcome financial hardships, but instead facilitated a growing economic divide and poor management decisions.
Collapse: Decreased precipitation rates, warmer temperatures and a self-interested short term

society spelled disaster for the Puget Sound region. Resource extraction and pollution load exceeded critical thresholds causing harm to ecosystem functions. Increased fragmentation and decreased precipitation led to droughts, forest fires and massive pest outbreaks. Increasing government costs and dwindling resources led to poor investments in infrastructure improvements and public services. As the beauty and health of the Puget Sound landscape slipped so did major industries, causing a severe economic depression followed by out-migration.
Adaptation: Despite major challenges caused by climate change, adaptive management and a positive consciousness regarding environmental change allowed the region to cope with the emerging problems and maintain high standards of life. Cooperation among residents, businesses and governmental units allowed this region to prosper despite increased vulnerability brought on by climatic impacts. Production rates decrease, but collective wealth rose due to investment is education, health and shared community resources such as public transit and renewable resource infrastructure. A growing awareness of future uncertainty embedded the precautionary principle into resource management and environmental policies, erring on the side of caution and increasing the region's resiliency.

An Approach to Selecting Ecosystem Indicators for Puget Sound

1. Background

What are ecosystem indicators and why are they useful?

Ecosystem indicators are quantitative biological, chemical, physical, social, or economic measurements that serve as proxies of the conditions of attributes of natural and socio-economic systems [28-31]. Ecosystem attributes are characteristics that define the structure, composition and function of the ecosystem that are of scientific and/or management importance, but insufficiently specific and/or logistically challenging to measure directly [28-31]. Thus, indicators provide a practical means to judge changes in ecosystem attributes related to the achievement of management objectives. They can also be used for predicting ecosystem change and assessing risk.

Terminology and Concepts

Indicators	Quantitative biological, chemical, physical, social, or economic measurements that serve as proxies of the conditions of attributes of natural and socioeconomic systems.
Key Attributes	Characteristics that define the structure, composition, and function of a Focal Component.
Focal Components	Major ecological characteristics of an ecosystem.
Goals	Combine societal values and scientific understanding to define a desired ecosystem condition.
DPSIR framework	Driver-Pressure-State-Impact-Response (DPSIR). Drivers are factors that result in pressures that cause changes in the system. Pressures are factors that cause changes in state or condition. State variables describe the condition of the ecosystem. Impacts measure the effect of changes in state variables. Responses are the actions taken in response to predicted impacts.

For more information and links to references, see Glossary

Ecosystem indicators are often cast in the Driver-Pressure-State-Impact-Response (DPSIR) framework—an approach that has been used by the PSP and broadly applied in environmental assessments of both terrestrial and aquatic ecosystems, including NOAA's Integrated Ecosystem Assessment [32]. *Drivers* are factors that result in pressures that cause changes in the system. Both natural and anthropogenic forcing factors are considered; an example of the former is climate conditions while the latter include human population size in the coastal zone and associated coastal development, the desire for recreational opportunities, etc. In principle, human driving forces can be assessed and controlled. Natural environmental changes cannot be controlled but must be accounted for in management. *Pressures* are factors that cause changes in state or condition. They can be mapped to specific drivers. Examples include coastal pollution, habitat loss and degradation, and fishing. Coastal development results in increased coastal armoring and the degradation of associated nearshore habitat. *State* variables describe the condition of the ecosystem (including physical, chemical, and biotic factors). Impacts comprise measures of the effect of change in these state variables such as loss of biodiversity, declines in productivity and yield, etc. *Impacts* are measured with respect to management objectives and the risks associated with exceeding or returning to below these targets and limits. *Responses* are the actions (regulatory and otherwise) that are taken in response to predicted impacts. Forcing factors under human control trigger management responses when target values are not met as indicated by risk assessments. Natural drivers may require adaptational response to minimize risk. For example, changes in climate conditions that in turn affect the basic productivity characteristics of a system may require changes in ecosystem reference points that reflect the shifting environmental states.

Ideally, indicators should be identified for each step of the DPSIR framework such that the full portfolio of indicators can be used to assess ecosystem condition as well as the processes and mechanisms that drive ecosystem health. State and impact indicators are preferable for identifying the seriousness of an environmental problem but pressure and response indicators are needed to know how best to control the problem [33]. However, because of time constraints, we opted to focus this initial draft of the PSSU on indicators of ecosystem state. Of course, the distinctions between pressure, state, and impact are often muddled and depend very much on perspective. For example, water quality is a primary goal of the PSP, and thus indicators of water quality provide information on the state of this goal. However, poor water quality is clearly a pressure that affects other states (e.g. species and food webs) and impacts (e.g. recreational fisheries). Thus, although we do not focus on driver, pressure and impact indicators, many are included in this section as well as the section on indicators of human health and well-being. It is also important to note that Chapters 1 and 2 of the PSSU are using indicators as tools to assess ecosystem status and condition, while Chapter 3 will focus on drivers and pressures of change to Puget Sound.

Relationship to previous indicator work in Puget Sound

The development of indicators for the Puget Sound ecosystem has a long history with different groups adopting slightly different frameworks to meet their varying goals [1, 34-40]. Here, we build upon the history of indicator work in the region, extending and adopting it to the current management setting in Puget Sound. We accomplish this in several ways. First, we propose a framework that links indicators to both PSP ecosystem recovery goals and the PSP performance management system. Additionally, we embrace and expand the criteria for indicator selection suggested by O'Neill et al. (2008) as part of their earlier indicator vetting for the PSP [34]. We also extend previous evaluations by considering potential indicators for which data are currently unavailable but are otherwise deserving of attention. Finally, while previous evaluations emphasized expert opinion, our approach focuses on peer-reviewed literature, supplemented by other sources of information.

In the 2008 Action Agenda, the PSP articulated six outcome statements that defined key attributes corresponding to each of the PSP ecosystem recovery goals [1]:

- Human health is supported by clean air and water, and marine waters and freshwaters that are safe to come in contact with. In a healthy ecosystem the fish and shellfish are plentiful and safe to eat, air is healthy to breathe, freshwater is clean for drinking, and water and beaches are clean for swimming and fishing.
- Human well-being means that people are able to use and enjoy the lands and waters of Puget Sound. A healthy ecosystem provides aesthetic values, opportunities for recreation, and access for the enjoyment of Puget Sound. Tribal cultures depend on the ability to exercise treaty rights to fish, gather plants, and hunt for subsistence, cultural, spiritual, ceremonial, and medicinal needs. The economic health of tribal communities depends on their ability to earn a livelihood from the harvest of fish and shellfish. Human well-being is also tied to economic prosperity. A healthy ecosystem supports thriving natural resource and marine industrial uses such as agriculture, aquaculture, fisheries, forestry, and tourism.
- Species are “viable” in a healthy ecosystem, meaning they are abundant, diverse, and likely to persist into the future. Harvest that is consistent with ecosystem conditions and is balanced with the needs of competing species is more likely to be sustainable. When ecosystems are healthy, non-native species do not impact the viability of native species or impair the complex functions of Puget Sound food webs.
- Marine, nearshore, freshwater, and terrestrial habitats in Puget Sound are varied and dynamic. The constant shifting of water, tides, river systems, soil movement, and climate form and sustain the many types of habitat that nourish diverse species and food webs. Human stewardship can help habitat flourish, or disrupt the processes that help to build it. A healthy ecosystem retains plentiful and productive habitat that is linked together to support the rich diversity of species and food webs in Puget Sound.
- Clean and abundant water is essential for all other goals affecting ecosystem health. Freshwater supports human health, use, and enjoyment. Instream flows directly support individual species and food webs, and the habitats on which they depend. Human well-being also depends on the control of flood hazards to avoid harm to people, homes, businesses, and transportation.
- Water quality in a healthy ecosystem should sustain the many species of plants, animals, and people that reside there, while not causing harm to the function of the ecosystem. This means pollution does not reach harmful levels in marine waters, sediments, or fresh waters.

In order to evaluate the status and condition of the ecosystem and progress towards recovery, it is necessary to have a more specific and structured list of attributes that define the characteristics of the ecosystem, as well as identify potential indicators for these attributes. Clearly, there is no shortage of potential indicators. However, an enormous challenge lies in winnowing down the catalog of candidate indicators to a manageable list that are most likely to faithfully track all of the important attributes of ecosystem health and, in so doing, enables further progress toward the PSP goals.

Our approach to selecting and evaluating a suite of indicators for the Puget Sound ecosystem was to: 1) develop a framework to describe the key ecosystem attributes of Puget Sound, organized by each of the PSP goals (Section 3.2), 2) select and organize potential environmental indicators according to the key ecosystem attributes (Section 3.2.3-3.24), 3) select a set of criteria to evaluate individual indicators (Section 4), and 4) evaluate the individual indicators according to a set of explicit criteria (Section 5) (see [41]). These steps will be described below.

A framework for selecting indicators within the management context of Puget Sound

Selecting a suite of indicators that accurately characterize the ecosystem, while also being relevant to policy concerns, is a significant challenge. A straightforward approach to overcoming this challenge is to employ a framework that explicitly links indicators to policy goals [42, 43]. This type of framework organizes indicators into logical and meaningful ways in order to assess progress towards policy goals. For example, Niemeijer and de Groot (2008) show that in the absence of an organizing framework, different indicators can be selected for the same environmental issue, even when evaluation criteria and data availability are similar [33]. Without a clearly defined link between the environmental issue (or policy goal) and the list of indicators, it becomes impossible to tell which set of indicators best characterizes the issue and why. Ideally, each indicator has a particular function or role in evaluating the status of an environmental concern. A well-defined and transparent framework clearly demonstrates why particular indicators were chosen (i.e., what function is fulfilled by each indicator), why others were ignored, and how the chosen set of indicators best address the environmental issue. Thus a framework is crucial for placing environmental issues and indicators into context so that indicators are selected based on analytical logic rather than individual indicator characteristics [33]. It also helps avoid redundancies and identifies gaps where indicators are needed.

In the 2008 Action Agenda, the PSP discussed the need for an organizing framework to analyze ecosystem information and provide an integrated assessment of the status of Puget Sound [1]. Several frameworks have since been developed by the Partnership, however no framework has been formally adopted [37]. Previous frameworks were developed based on general recommendations and guidance in the Open Standards for the Practice of Conservation, and reports by the U.S. EPA, and the Heinz Center [3, 42, 44]. We have drawn upon these documents, as well as Harwell et al. (1999), to develop a broad, hierarchical framework to guide our evaluation of Puget Sound ecosystem indicators [43].

A guiding principle in the development our framework was that it should be reflective of societal goals and values, and be policy-relevant [3, 41-43]. The clearest guidance available for values and policy relevance are the six statutory goals defined by the PSP. Our framework thus begins with these six Goals. We then decompose these goals into unique ecological Focal Components within specific habitat domains (i.e., marine, freshwater, terrestrial, and interface/ecotone). Each focal component is characterized by Key Attributes, which describe fundamental aspects of each focal component. Finally, we map Indicators onto each ecosystem key attribute (Figure 2). Each tier of this framework is detailed below.

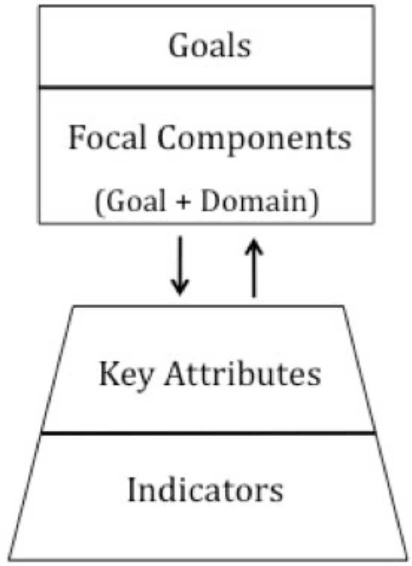


Figure 2. Proposed framework organization for assessing and reporting on ecosystem condition in Puget Sound.

Tier 1: Goals.

The broadest category of division of our framework is Goals. Goals combine societal values and scientific understanding to define a desired ecosystem condition [42, 43]. Explicit descriptions of the societal values related to the condition of Puget Sound are encompassed in the six statutory goals developed by the PSP [37], as shown in Section 3.1.3.

These goals reflect both societal and ecological interests in Puget Sound, and have been used as the fundamental organizing framework for assessing a 'healthy' Puget Sound ecosystem in the Partnership Action Agenda [37]. They are policy-relevant, which is foundational in the development of this framework. Note that for the purposes of indicator evaluation, we separated "Species" and "Food Webs." This section focuses only on natural ecosystem components. Thus, human health and human well-being are addressed elsewhere in the PSSU.

Tier 2: Focal Components.

Focal Components are the major ecological characteristics of an ecosystem that can be used to organize relevant information in a limited number of discrete, but not necessarily independent categories [3]. In the Open Standards for the Practice of Conservation they are referred to as, 'focal conservation targets.' The term 'Focal Component' has been used previously by the PSP [37] and has been adopted here to keep terminology consistent.

Focal Components were derived by dividing each of the Goals into distinct habitat domains that are characterized by unique qualities or traits. The domains we chose were marine, freshwater, terrestrial, and interface/ecotone. The interface/ecotone domain includes zones with a combination of traits from the other major groups such as the nearshore environment, wetlands, and estuaries.

This grouping (Table 2) provides a comprehensive view of the major ecological characteristics of Puget Sound based on area, and allows Focal Components to be assessed at an individual level (e.g., marine habitats), or aggregated into a single environment (e.g., assessing the integrity of the marine environment across all marine-related Focal Components).

Table 2. Summary of Focal Components based on goal and domain.

Goal	Domain	Focal Component
Species	Marine	Marine Species
	Freshwater	Freshwater Species
	Terrestrial	Terrestrial Species
	Interface/Ecotone	Interface Species
Food Webs	Marine	Marine Food Webs
	Freshwater	Freshwater Food Webs
	Terrestrial	Terrestrial Food Webs
	Interface/Ecotone	Interface Food Webs
Habitats	Marine	Marine Habitats
	Freshwater	Freshwater Habitats
	Terrestrial	Terrestrial Habitats
	Interface/Ecotone	Interface Habitats
Water Quality	Marine	Marine Water Quality
	Freshwater	Freshwater Quality
	Interface/Ecotone	Interface Water Quality
Water Quantity	Freshwater	Freshwater Quantity

Tier 3: Key Attributes.

Key Attributes are ecological characteristics that specifically describe the state of Focal Components. They are characteristic of the health and functioning of a focal component. They are explicitly defined based on each Focal Component and provide a clear and direct link between the Indicators and Focal Components. A similar tier has been identified by the PSP and others. A part of our framework development was an explicit comparison of the Key Attributes developed here with those suggested in the other reports. Although they differ in detail, the Key Attributes adopted here encompass all those identified by the EPA (2002), Heinz Center (2008), and the PSP [37, 42, 44]. Selected Key Attributes are shown in Table 3.

Table 3. Selected key attributes for each goal. Definitions (or measures) are meant to describe what is meant by each attribute. For example, population size is represented by the number of individuals in a population or the total biomass.

Goal	Key Attribute	Relevant Measures
Species	Population Size	Number of individuals or total biomass; Population dynamics
	Population Condition	Measures of population or organism condition including: Age structure; Population structure; Phenotypic diversity; Genetic diversity; Organism condition
Food Webs	Community Composition	Species diversity; Trophic diversity; Functional redundancy; Response diversity
	Energy and material flow	Primary production; Nutrient flow/cycling
Habitats	Habitat Area & Pattern/Structure	Area or extent; Measures of pattern/structure including: Number of habitat types; Number of patches of each habitat; Fractal dimension; Connectivity
	Habitat Condition	Abiotic & biotic properties of a habitat; Dynamic structural characteristics; Water & benthic condition
Water Quality	Hydrodynamics	Measures such as: Water movement; Vertical mixing; Stratification; Hydraulic residence time; Replacement time
	Physical/Chemical Parameters (Sediments & Water Column)	Measures such as: Nutrients; pH; Dissolved oxygen/redox potential; Salinity; Temperature
	Trace Inorganic & Organic Chemicals (Sediments & Water Column)	Measures such as: Toxic contaminants; Metals; Other trace elements & organic compounds
Water Quantity	Surface Water	Hydrologic Regime Measures such as: Flow magnitude & variability; Flood regime; Stormwater
	Groundwater Levels & Flow	Groundwater accretion to surface waters; Within groundwater flow rates & direction; Net recharge or withdrawals; Depth to groundwater
	Consumptive Water Use & Supply	Water storage

We reduced the list of potential attributes for each Goal and Focal Component to two or three Key Attributes for two reasons. First, this approach is driven by a need for simplicity, succinctness, and transparency in the development of an organizing framework. Second, the use of only 2-3 attributes for each Goal and Focal Component provides a means to address data gaps in the selection and evaluation of indicators. By defining the key attributes broadly, our framework allows for situations in which a single attribute (e.g., population condition for the Species Goal) can be informed by multiple types of indicators depending on information availability (e.g., population condition can be tracked using data on disease for some species, data on age structure for others, etc.).

A discussion of the Key Attributes for each goal follows.

Key Attributes – Species

A central goal identified by the PSP is to have 'healthy and sustaining populations of native species in Puget Sound' that provide ecosystem goods and services to humans, and support the structure and functioning of the ecosystem itself [1]. Many different attributes can describe whether a population is 'healthy and sustaining'. For example, the U.S. EPA (2002) identified eight different measures (i.e., attributes) of species condition including population size, genetic diversity, population structure, population dynamics, habitat suitability, physiological status, symptoms of disease or trauma, and signs of disease [42]. Similar attributes identified by Fulton et al. (2005) included biomass, diversity, size structure, and spatial structure [45]. Niemi and McDonald (2004) suggest attributes based on type, for example, structural attributes include genetic structure and population structure whereas functional attributes include life history, demographic processes, genetic processes, and behavior [46].

Historically the PSP has focused on population size as the species attribute, recognizing that species health or condition was encompassed by most other PSP goals [40]. More recently the PSP identified species key attributes by applying the Open Standards to the Action Agenda [37]. The species attributes they selected were forage fish, condition of key fish populations, population size and condition of key marine shellfish and invertebrates, population size and condition of key marine mammals, population size and condition of key marine birds, extent of all salmon species, condition of all listed salmon species, spatial structure of all listed salmon species, and population size and condition of key terrestrial bird species [37].

Population size is defined as the number of individuals in a population or the total biomass of the population. Population dynamics that influence changes in abundance over time are also included. Population condition combines several measures: population structure, age structure, genetic diversity, phenotypic diversity, and organism condition.

Selection of Species Attributes in Puget Sound

Ecological attributes are intended to describe the state of an ecological system; in the case of species attributes, they are meant to describe the condition or viability of populations of species in an area. Measures of population condition or viability are important indicators, yet monitoring the status of all species is practically impossible. To address this, focus should be placed on identifying species indicators that characterize key interests in the region (i.e., focal species). For example, some species exert a disproportionately important influence on ecosystem condition, while others relate to biodiversity or are of direct interest to society. Examples of focal species include target, charismatic, vulnerable, and strongly interacting species. Target species are those fished or harvested for commercial gain or subsistence. Flagship species are those with widespread public appeal that are often used to communicate to the public about the condition of the ecosystem. Vulnerable species are those recognized with respect to their conservation status, for example, threatened, endangered, or of greatest conservation concern. Strongly interacting species (e.g., keystone species) are those whose presence, absence or rarity leads to significant changes in some feature of the ecosystem (adapted from [47, 48]).

The following sections provide examples of the utility of population size and population condition in evaluating the status of focal species as well as ecosystem health.

Population size

Monitoring population size, in terms of total number of individuals or total biomass, is important for management and societal interests. For example, abundance estimates are used to track the status of threatened and endangered species and help determine whether a species is recovering or declining. Accurate estimates of population biomass of targeted fisheries species are used to assess stock viability and determine the number of fish that can be sustainably harvested from a region. While population size can be used to assess population viability, more accurate predictions of viability can be obtained by including the mechanisms responsible for the dynamics of the population. Population dynamics thus provide a predictive framework to evaluate the combined effect of multiple mechanisms of population regulation (e.g., birth and death rates, immigration and emigration) to evaluate changes in abundance through time.

Population condition

Whereas the preceding attribute is concerned with measures of population size, there are instances when the "health" of the population may be of interest. For example, monitoring changes in population condition may presage an effect on population size or provide insight into long-term population viability. The dynamics of many populations are better understood through knowledge of population condition such as organism condition, age structure, genetic diversity, phenotypic diversity, and population structure. Impaired condition of any or all of these subcategories indicates biological resources at risk. In addition, monitoring changes in organism condition can be used to infer changes in environmental conditions.

Organism condition

Organism condition represents both physiological and disease status. Monitoring organism condition may help predict changes in population size, and reveal environmental problems that warrant management action. Past efforts by the PSP have focused on organism condition (e.g., toxins in harbor seals) as an indicator of Water Quality. While this may be applicable for organisms at lower trophic levels (i.e., because they respond at shorter temporal scales), but time lags associated with the transfer of toxins through the food web means that higher trophic level organisms (e.g., killer whales, sixgill sharks) are unlikely to reveal Water Quality issues at time scales relevant to management. We suggest these measures (e.g., toxins in killer whales) are better served as an indicator of species population condition.

Physiological status is the key mechanism linking both organism and population to their environment [49]. For example, individuals experiencing increased environmental stress may increase levels of stress hormones, eventually killing the individuals and leading to a decrease in population size. In the Galapagos, marine iguanas increased stress hormone levels due to fouling from an oil spill. The increase in stress hormone levels predicted a decrease in survival by approximately fifty percent, which was later confirmed by field studies [50]. Disease status can affect population size and dynamics as well. In Prince William Sound, viral hemorrhagic septicemia virus (VHSV) was linked to a reduction in Pacific herring recruitment [51]. A recent paper by Landis and Bryant (2010) suggests that disease prevalence in Puget Sound was a contributing factor to the decline of Pacific herring (Cherry Point, Squaxin Pass, Discovery Bay, and Port Gamble stocks) in the 1970s and 1980s [52]. Thus, monitoring organism condition may signal declines in population abundance before it occurs.

Monitoring organism condition is particularly important for long-lived organisms (e.g., marine mammals, rockfish) that live in contaminated habitats. Declines in population size of long-lived species may be slow to appear because of their long cohort turnover times. The temporal scale at which this occurs makes it difficult to recognize the population is in decline, and respond fast enough to prevent severe changes in population dynamics [53]. Declining organism condition from contaminant exposure can also interact with diseases so that individuals in poor physiological condition are more susceptible to infections [54]. In juvenile salmon, exposure to contaminants lead to increased disease susceptibility, significantly reducing population size [55].

Finally, examining the physical condition of a population may reveal problems with current management strategies. For example, salmon injured by gillnets show reduced survival and fail to reproduce; this suggests estimates of spawning stocks, which count injured fish as part of the aggregate escapement of viable spawners, are inflated [56].

The remaining subcategories of population condition (i.e., age structure, population structure, genetic diversity, and phenotypic diversity) are primarily used for assessing focal species condition, and generally do not present information relating to environmental conditions. Due to this reason, these subcategories are discussed in terms of relevance to focal species.

Age structure

Population age structure is used to estimate population viability by modeling population trends through time, and can be especially useful for evaluating the long-term stability of a population. Monitoring age structure may also be useful in attributing declines in abundance to specific factors, which may otherwise be difficult to detect.

Robust age structure (i.e., multiple reproductive age classes) is critical for fish populations to withstand environmental variability and maintain resilience. Multiple reproductive age classes provide resilience for several reasons: (1) overall reproductive output increases, (2) age-related differences in spawning locations and timing allocate reproductive outputs across larger spatial and temporal areas, and (3) there is increased quantity and quality of eggs produced by older fish [57, 58]. Fisheries often target large and therefore old individuals, effectively truncating the age structure of the population. This is likely to reduce population resilience.

In order to attribute declines in stellar sea lion (SSL) populations to specific factors, age-structure information is required to separate out vital rate changes from population abundance estimates [59]. For example, a risk factor (e.g., contaminants) may affect an age-specific vital rate but show no corresponding change in population abundance. Examining age-structure trends may provide insight into population declines of various species in Puget Sound (e.g., Southern

Resident Killer Whales, Pacific herring, rockfish) or elucidate factors that affect age-specific organism condition.

Genetic diversity

Genetic diversity measures may be important in assessing long-term population viability, as well as the ability for a population to adapt to changing environmental conditions. Monitoring genetic loci or gene expression may also help detect the onset of selection events such as emerging diseases, climate change or land use change, or pollution [60].

Although not always the case [61], loss of genetic variation can reduce individual fitness (e.g., through loss of heterozygosity), as well as the ability of populations to evolve in the future (e.g., through loss of allelic diversity) [62]. For example, in Greater Prairie Chickens loss of genetic variation was linked with lower hatching success of eggs following population declines [63]. Genetic changes (e.g., declines in fecundity, egg volume, larval size, etc.) caused by overharvesting fish populations can increase extinction risks and reduce the capacity for population recovery [64].

Phenotypic diversity

Individual organisms adapt to changing environmental conditions by sensing the changes and responding appropriately, for instance, by switching their behavior or physiology. However this means that every individual must reserve a portion of their energy to actively sensing and adapting to environmental changes. An alternative strategy is to diversify a population: each subset of the total population is adapted to a slightly different environmental condition (i.e., phenotypic diversity). Sockeye salmon, for example, show a suite of adaptations to the diversity of spawning habitats. This phenotypic diversity has proven to be critical under changing environmental conditions in Bristol Bay, Alaska. As conditions changed, populations demonstrated differential responses so that at different times, different populations became more productive [65]. In California, the development of the Sacramento-San Joaquin watershed has truncated the life history diversity of Chinook salmon, resulting in the collapse of these populations [66]. Recognizing and understanding phenotypic diversity may prevent the loss of population subsets that currently appear unproductive, but may prove vital for long-term population sustainability.

Population structure

Population structure refers to spatial dynamics, or how different populations interact in space. In many instances local populations are linked, thereby creating a metapopulation. When environmental conditions change, some populations decline while others persist, but the overall density of the metapopulation may remain relatively steady. Metapopulations persist through a suite of adaptations at the individual (e.g., physiological and behavioral adaptations) and population level (e.g., each subpopulation lives in a separate location and contains distinct demographic parameters). Understanding the spatial variation of populations, how they interact, and how demographic parameters differ among these populations are essential to sound management of focal species.

For example, sedentary stocks such as benthic invertebrates are typically structured as metapopulations; the subpopulations stay connected through larval or juvenile dispersal. The strong spatial effects not only make it difficult for a population to persist on its own, but adding in pressure from fishing has the chance to lead to stock depletion [67]. In Bristol Bay, sockeye salmon populations exist as mixed stocks (i.e., a metapopulation stock complex) during their adult phase. Management of salmon has historically focused on the metapopulation stock complex, rather than concentrating on the most productive populations. As a result, sockeye salmon harvest has remained relatively stable over decades. In the conservation of threatened species it is important to recognize that single populations have a high risk of extinction, and effectively managing for species persistence requires a metapopulation-level approach. For example, recovery strategies for Puget Sound Chinook salmon recommend two to four viable subpopulations within each geographic region to reduce the risk of extinction for the metapopulation [68].

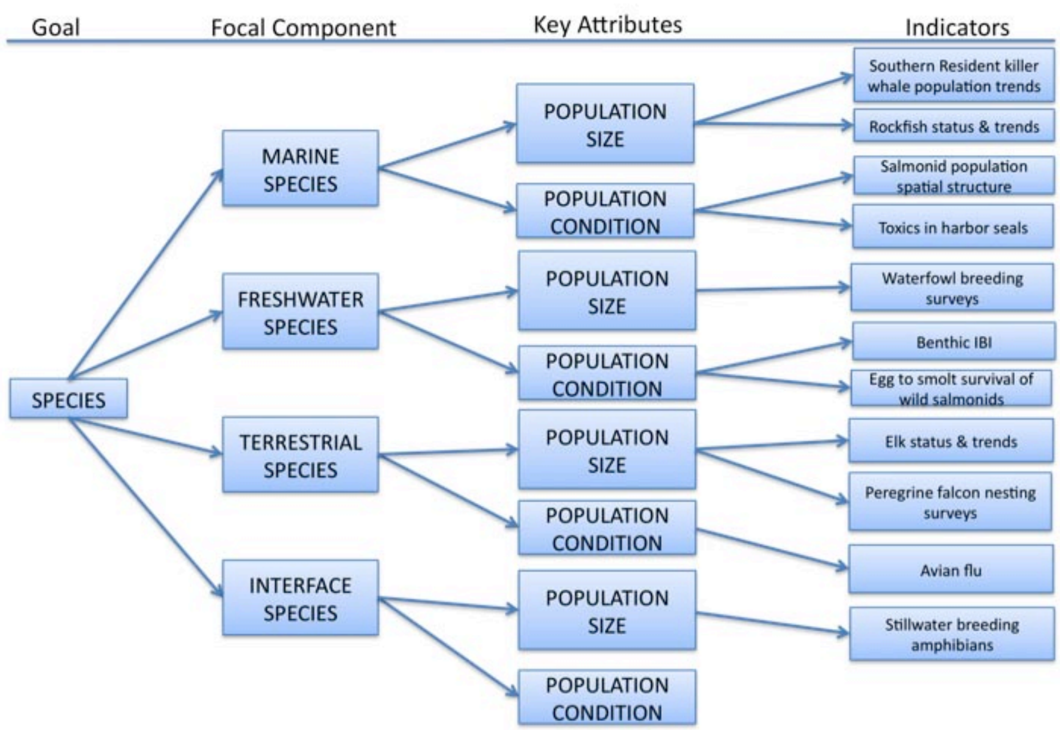


Figure 3. Summary of framework organization for Species goal. The list of indicators is illustrative only, and not complete.

Key Attributes – Food Webs

The food web indicator evaluations focused on two key attributes: (1) community composition, and (2) energetics and material flows. These two attributes reflect the structure and function of a food web and were drawn from a large literature on the subject [42, 69-74]. Food web attributes provide a measure of the extent to which different components of the ecosystem interact (e.g., habitats and species) along with important contextual information for understanding the status of the individual components themselves.

We have adopted a broad definition of community composition that includes species diversity, trophic diversity, functional redundancy, and response diversity. This definition is consistent with "community attributes," a key attribute for food webs recently designated by the PSP [37]. Species diversity encompasses species richness, or the number of species, in the food web, and species evenness, or how individuals or biomass are distributed among species within the food web [69]. Trophic diversity refers to the relative abundance or biomass of different primary producers and consumers within a food web [42]. Consumers include herbivores, carnivores or predators, omnivores, and scavengers. Functional redundancy refers to the number of species characterized by traits that contribute to a specific ecosystem function, whereas response diversity describes how functionally similar species respond differently to disturbance [75]. For example, a food web containing several species of herbivores would be considered to have high functional redundancy with respect to the ecosystem function of grazing, but only if those herbivorous species responded differently to the same perturbation (e.g., trawling) would the food web be considered to have high response diversity.

Like community composition, the second key attribute of food webs, energy and material flows, was previously highlighted by the PSP [37]. This attribute includes ecological processes such as primary production and nutrient cycling, in addition to flows of organic and inorganic matter throughout a food web. Primary productivity is the capture and conversion of energy from sunlight into organic matter by autotrophs, and provides the fuel fundamental to all other trophic transfer in a food web. Material flows, or the cycling of organic matter and inorganic nutrients (e.g., nitrogen, phosphorus), describe the efficiency with which a food web maintains its structure and function.

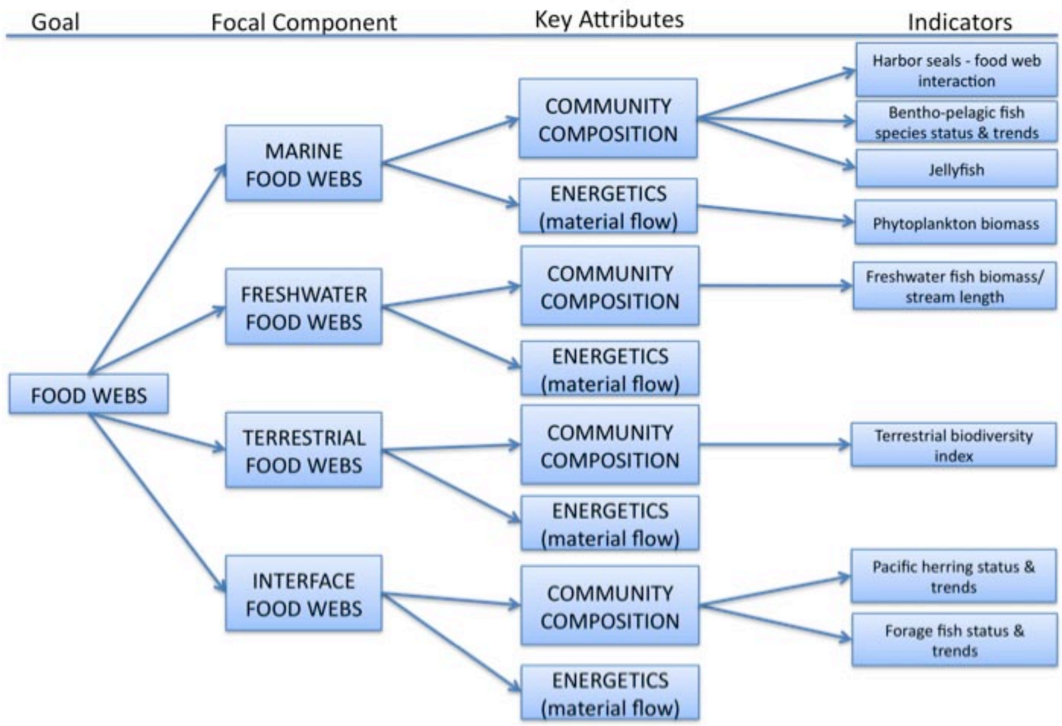


Figure 4. Summary of framework organization for Food Webs goal. The list of indicators is illustrative only, and not complete.

Key Attributes – Habitats

The Puget Sound basin encompasses diverse marine, nearshore, freshwater, and terrestrial habitats. As such, a key goal of the PSP is to have ‘a healthy Puget Sound where freshwater, estuary, nearshore, marine, and upland habitats are protected, restored, and sustained’ (from RCW 90.71.300). Many different ecological attributes may be used to describe habitat status and determine whether or not it is ‘healthy’. The U.S. EPA (2002) identified various attributes of habitats (referred to as ‘landscapes’) including extent, composition, and pattern/structure; other attributes of habitats included dynamic structural characteristics and physical structure [42]. The U.S. EPA also acknowledged habitat condition, but recommended its use as a species attribute (i.e., habitat suitability) because they defined condition in terms of the organisms of interest [42]. Similar landscape attributes identified by the Heinz Center (2008) included extent and pattern [44].

In 2009, the PSP structured their reporting on ecosystem status around two broad indicator categories for the habitat goal: extent and condition of ecological systems [37]. These broad categories were selected to represent key attributes associated with the habitat goal [37], and were used to report on extent and condition of focal habitats in Puget Sound [76]. Simultaneously, a PSP working group identified several key habitat attributes including: estuarine wetlands, delta or river mouth condition, coastal embayments and lagoons, forage fish spawning habitat/substrate, condition of shorelines and condition of beaches, benthic condition, marine water condition, freshwater condition, spatial extent of ecological systems (terrestrial), condition of ecological systems or plant associations (terrestrial), and functional condition for key terrestrial species [37].

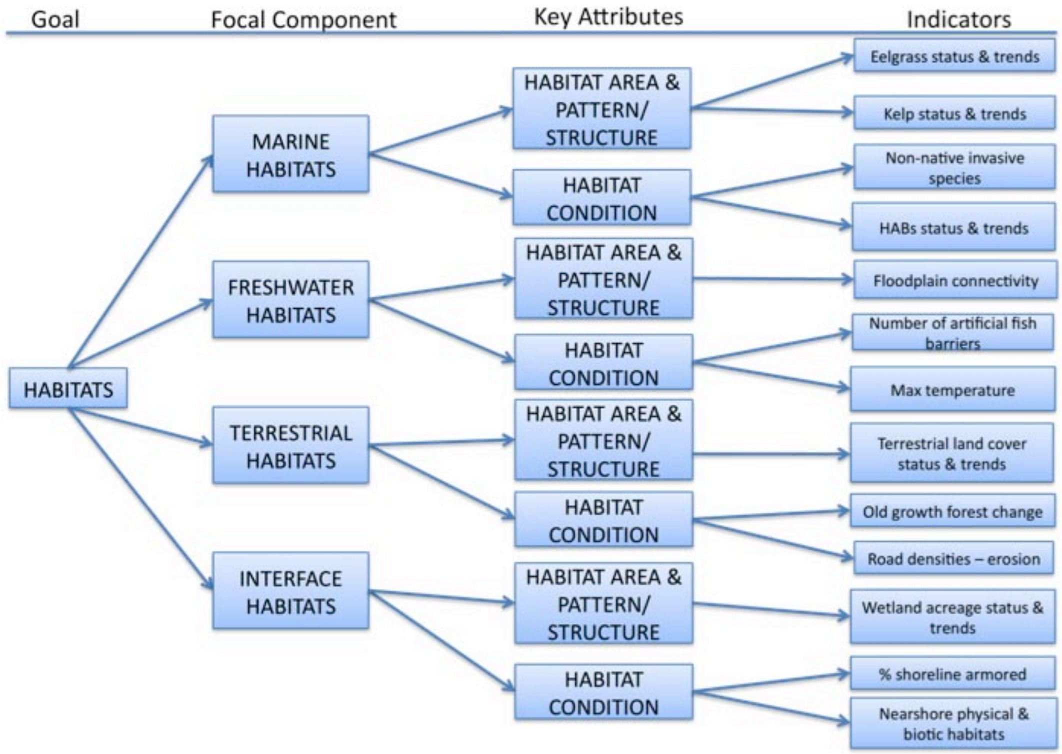


Figure 5. Summary of framework organization for Habitats goal. The list of indicators is illustrative only, and not complete.

Habitat area and pattern/structure combines several measures. Habitat area is defined as the areal extent and shape of each habitat type. Pattern/structure refers to the number of habitat types, the number of patches of each habitat, fractal dimension (i.e., habitat complexity), and connectivity. Habitat condition refers to abiotic properties (i.e., physical and chemical properties) and biotic properties (e.g., invasive or nuisance species, dominant species). Dynamic structural characteristics (i.e., changes in physical habitat complexity and morphology) are also included in habitat condition because they maintain the diversity of natural habitats. Water quality and benthic condition also contribute to habitat condition; however, according to the PSSU framework, they fall under the Water Quality goal and will therefore be discussed in that section.

Key Attributes – Water Quality

The purpose of the framework development with regard to indicator selection, was to ensure that there was complete coverage of the goals by the indicators. The first division of goals was into ecologically unique domains (e.g., marine water, freshwater, and ecotones), which defined the Key Attributes. The properties of the Key Attributes must be known in order to define the state of that aspect of the ecosystem. Key attributes must be managed in order to sustain each conservation target (i.e. focal components) [77, 78]. This approach is similar to that previously utilized by the PSP [37].

There are three key attributes, which articulate Water Quality: hydrodynamics, the physical and chemical parameters, and trace inorganic and organic contaminants. These key attributes for water quality have also been utilized elsewhere [42, 43, 79].

Hydrodynamics are important characteristics of water quality in marine, freshwater, and transitional (e.g., wetlands, estuaries, etc.) systems. River and stream hydrodynamics are defined by various aspects of the flow regime including magnitude, frequency, duration, timing, and rate of change. Each of these has important impacts on ecology and human health and well-being [80-83]. The hydrodynamics of river and stream is discussed in the Water Quantity section of this Puget Sound Science Update. Lake hydrodynamics are generally defined by mixing, stratification (i.e. the lack of mixing), and residence times. All of these are key aspects of nutrient cycling and can be deterministic in lake water quality [84, 85]. Hydrodynamics are also important in marine environments. Offshore circulation patterns and seawater intrusions into Puget Sound bring in nutrient rich waters, which can impact eutrophication and dissolved oxygen (see Chapter 2 of the Puget Sound Science Update; [86-90]). Rivers and streams entering Puget Sound create areas of density stratification, which can also affect eutrophication [90, 91]. Hydrodynamics are critical in understanding water quality and have been incorporated as a Key Attribute.

Physical and chemical parameters are also crucial in determining water quality. The suitability of freshwater and marine water systems to support biota is strongly dependent on temperature and dissolved oxygen (DO; see [92, 93] and references therein). Low DO is an issue of management importance in the Hood Canal and the south Puget Sound [94]. The level of nutrients such as nitrogen and phosphorus in lakes and estuaries can affect primary productivity and habitat quality [86, 95-101]. Anthropogenic nutrient inputs have been associated with harmful algal blooms (see Chapter 2 of the Puget Sound Science Update; [102]). Increasing levels of atmospheric carbon dioxide in the may lead to decreased pH with ocean acidification, potentially resulting in severe impacts on key marine organisms with calcium carbonate exoskeletons [103]. General physical and chemical parameters are of import in defining water quality and are, thus, utilized as Key Attributes.

The presence and concentrations of trace organic and inorganic chemicals, also known as toxics, contaminants, pollutants, etc., may have impacts of the human health and the environment. Much of the implementation of the Clean Water Act has focused on the reduction of chemicals into surface waters for "the protection and propagation of fish, shellfish, and wildlife and recreation in and on the water" [104]. A discussion of the toxic contaminants in Puget Sound is included in Chapter 2 of this Puget Sound Science Update, and also Section 5.4. Due to their potential importance both ecologically and to human-well being, trace organic and inorganic chemicals is a Key Attribute of water quality.

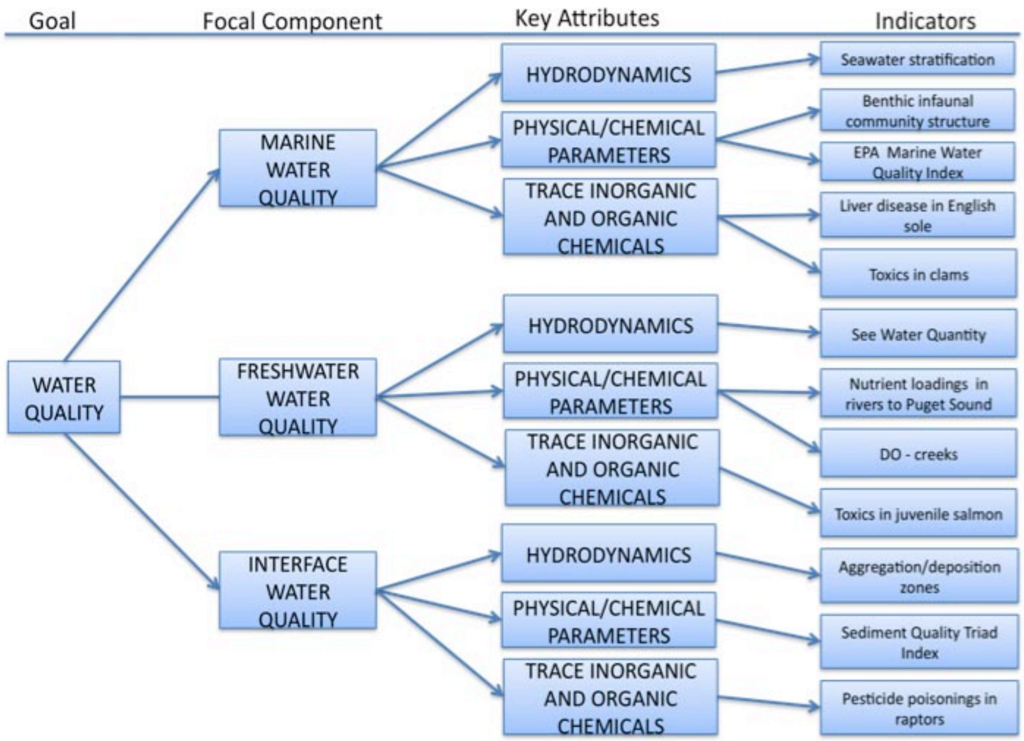


Figure 6. Summary of framework organization for Water Quality goal. The list of indicators is illustrative only, and not complete.

Key Attributes – Water Quantity

In order to evaluate indicators of water quantity, we used three distinct Key Attributes: the surface water hydrologic regime, groundwater levels and flows, and consumptive water use and supply. The PSP has utilized other organizational frameworks though they selected similar attributes. In the 2009 document, "Identification of Ecosystem Components and Their Indicators and Targets," water quantity was not dealt with as an explicit goal but rather as supportive of habitats and human uses [37]. This resulted in the selection of freshwater extent, freshwater condition, and water supply for end users as attributes – all similar to the Key Attributes used herein. The EPA defined surface and groundwater flows as an essential ecosystem attribute category with subcategories including pattern of surface flows, hydrodynamics, and pattern of groundwater flows [42]. Their framework focused on ecological condition and did not explicitly include human dimensions. The Heinz Center reports on the extent of freshwater ecosystems, changing stream flows, water withdrawals, and groundwater levels [44]. Other studies have reported the use of similar attributes to define the state of water quantity [105].

The surface water hydrologic regime has important impacts on the regional ecosystems (see [80] and references, therein). The groundwater is an important source both for consumptive use and river and stream base-flows. Consumptive water use and supply are important measures of resource conservation and supply and relate strongly to the human health and well-being of the region.

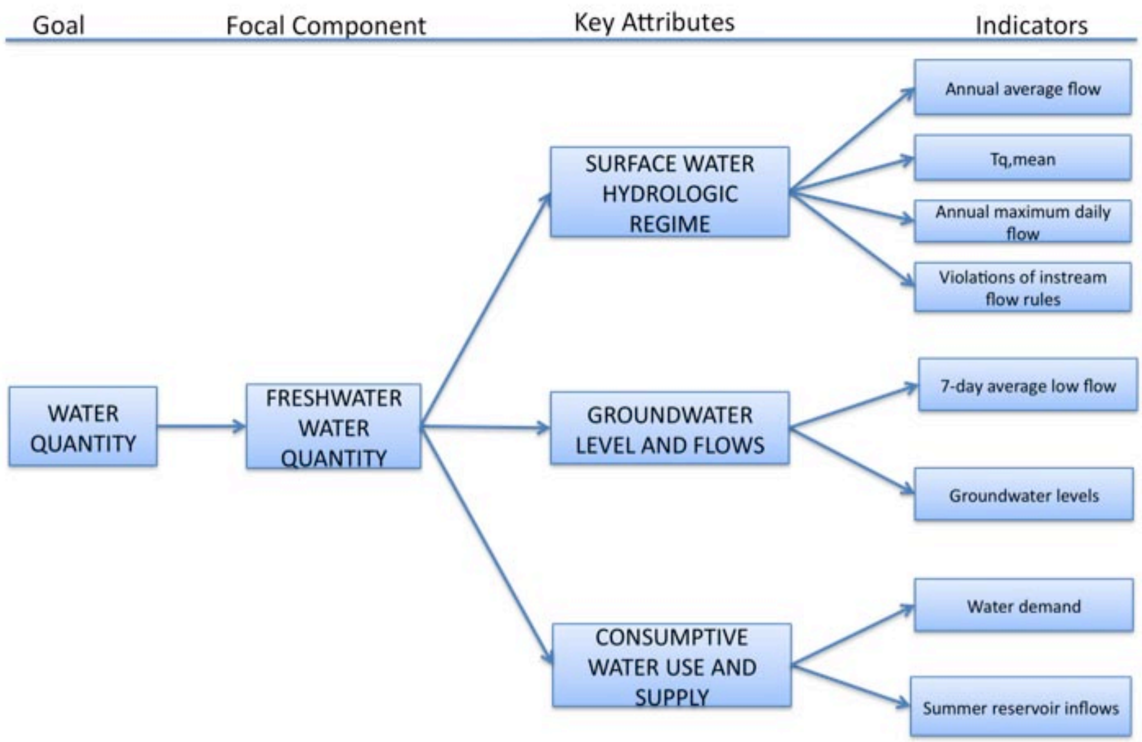


Figure 7. Summary of framework organization for Water Quantity goal. The list of indicators is illustrative only, and not complete.

Tier 4: Indicators.

Indicators are metrics that reflect the structure, composition, or functioning of an ecological system [42, 44]. Indicators are measurable characteristics that can assess changes in ecosystem attributes. A list of candidate indicators was selected from several sources (see Section 4.1) and each indicator was assigned to a specific Key Attribute based on expert opinion. Indicator identification and evaluation is discussed in Section 4.

A conceptual framework for selecting indicators of ecosystem condition is valuable for several reasons. First, indicators are often selected based on the degree to which they meet a number of criteria individually, rather than on the basis of how they collectively assess ecosystem condition [33]. A conceptual framework explicitly includes the inter-relation of indicators as part of the indicator selection process, and helps to develop consistent indicator sets [33]. Second, a conceptual framework provides flexibility. For example, if the goal is to assess marine ecosystem health using only ten indicators, a hierarchical framework provides a way to select indicators so that all the relevant ecosystem components are included. In this case, one to three indicators would be selected from Marine Species, Marine Food Webs, Marine Habitats, and Marine Water Quality in order to ensure adequate representation of all the important features. Third, a framework highlights indicators that may be relevant to multiple goals, focal components, or attributes. For example, the population abundance of Western sandpipers is related to the Species goal, but may also be relevant to the Habitats goal if their abundance reflects changes in habitat condition. Finally, a framework explicitly links indicators→attributes→ focal components→goals, which ensures sufficient coverage of the Key Attributes essential to each goal. A conceptual framework provides a structured yet flexible way to select indicators that best represent the environmental issue at hand.

Key point: A carefully crafted framework provides a robust means for assuring that ecosystem indicators are explicitly linked to societal goals. The approach we present melds a number of separate PSP activities into a single, transparent framework and provides a structured yet flexible means to select ecologically and socially meaningful indicators.

Evaluation of Potential Indicators for Puget Sound

1. Indicator selection and organization

We began our evaluation of indicators by compiling a list of available indicators. To build on previous efforts, we selected indicators from three sources: a 2008 report titled, "Environmental Indicators for the Puget Sound Partnership: A Regional Effort to Select Provisional Indicators (Phase 1);" the PSP Action Agenda; and the 2009 PSP Technical Memoranda, "Identification of Ecosystem Components and Their Indicators and Targets," and "Ecosystem Status and Trends" [1, 34, 37, 76]. Further, a small number of indicators were identified through a review of the regional literature (e.g., [23, 106]) and were also included on the list of available indicators.

The authors of the "Environmental Indicators for the Puget Sound Partnership" report reviewed over 100 documents to create a list of more than 650 indicators that had been proposed or used in Puget Sound and Georgia Basin [34]. Using a set of screening criteria, they reduced the list to approximately 250 indicators that were "good," or "potential." Further, there was a set of indicators, which were of, "possible future," value but were not considered for use in that evaluation because they did not have existing data. However, they were included in our evaluation. Finally, there was a small group of indicators indentified that were not evaluated in the 2008 work. These were also included in the PSSU process.

The PSP Action Agenda listed a subset of environmental indicators, which had been selected based on a review by the PSP Science Panel [1]. This list of 102 indicators was included in our evaluation process to ensure completeness.

In 2009, the PSP began a separate indicator selection process specifically guided by the Open Standards for the Practice of Conservation [3, 37] which included the development of Focal Components and Key Attributes through a series of workshops. As summarized in the 2009 Technical Memorandum, "Identification of Ecosystem Components and Their Indicators and Targets," the process resulted in the identification of over 160 indicators, including many associated with the Built Environment, Working Marine Industries, Working Resource Lands and Industries, Nature Oriented Recreation, and Aesthetics, Scenic Resources, and Existence Values [37]. These indicators were included in our evaluation, unless they had been previously evaluated and found to be theoretically unsound [34].

In a parallel effort, the PSP Technical Memorandum, "Ecosystem Status and Trends," reported on a set of 43 indicators [107]. A subset of these were used in the 2009 State of the Sound report. All were included for consideration.

Finally, with specific regard to the indicators of Water Quantity, the literature identifies well over 150 unique indicators, which can be utilized to track various aspects of the hydrologic flow regime (see [108]). Instead of individually evaluating each indicator, a literature review was undertaken to identify issues of potential concern in the Puget Sound region (see Section 5.5) and the results of that literature review were used to focus the choice of Water Quantity indicators for further evaluation.

The entire set of indicators was combined and redundant indicators removed, yielding a composite list of over 250 preliminary indicators for evaluation. The indicators were then organized according to the Key Attributes of our framework (see Figure 2 in Section 3). Our initial organization was based solely on expert opinion and recommendations. The process identified several indicators that could be appropriately categorized under more than one Key Attribute. However, the evaluation process allowed for the reorganization or reassignment of indicators based on the results of the review of the literature.

Once organized, each individual indicator was evaluated against a set of evaluation criteria, as described below. Importantly, the aim of this process was to support the science-policy processes of the PSP by evaluating the degree to which indicators meet

Indicator Evaluation Criteria

There exist nearly as many guidelines and criteria for developing and selecting individual indicators as there exist indicators. The summary of criteria for relevant and reliable indicators builds on the recommendations in the indicator report to the PSP [34], and is based on [29, 30, 33, 41, 43, 109-115]. These criteria apply to indicators of ecosystem state, the focus of this chapter. However, the approach and criteria we develop here is immediately transferable to the rigorous evaluation of driver and pressure indicators as well.

We divide indicator criteria into three categories: primary considerations, data considerations, and other considerations. Primary considerations are essential criteria that should be fulfilled by an indicator in order for it to provide scientifically useful information about the status of the ecosystem in relation to PSP goals. Data considerations relate to the actual measurement of the indicator. Data considerations criteria are listed separately to highlight ecosystem indicators that meet all or most of the primary considerations, but for which data are currently unavailable. Other considerations criteria may be important but not essential for indicator performance.

Other considerations are meant to incorporate non-scientific information into the indicator evaluation process. Ecosystem indicators should do more than simply document the decline or recovery of ecosystem health, they must also provide information that is meaningful to resource managers and policy makers [8]. Because indicators serve as the primary vehicle for communicating ecosystem status to stakeholders, resource managers, and policymakers, they may be critical to the policy success of EBM efforts, where policy success can be measured by the relevance of laws, regulations, and governance institutions to ecosystem goals. Importantly, policy success does not necessarily produce effective management since it is possible to be successful at implementing poor policy. Nonetheless, advances in public policy and improvements in management outcomes are most likely if indicators carry significant ecological information and resonate with the public.

It should be noted that all of the criteria listed need not be weighted equally, nor is it necessary to meet all of the criteria for an indicator to be valuable or of use for a specific application. Scientifically credible indicators should meet the “primary considerations” we outline below, and that further selection and evaluation be based on local needs and guided by the data and other considerations. A discussion of potential ranking is in Section 5.6.

The criteria we used are as follows:

Primary considerations

1. **Theoretically-sound:** Scientific, peer-reviewed findings should demonstrate that indicators can act as reliable surrogates for ecosystem attribute(s)
2. **Relevant to management concerns:** Indicators should provide information related to specific management goals and strategies.
3. **Responds predictably and is sufficiently sensitive to changes in a specific ecosystem attribute(s):** Indicators should respond unambiguously to variation in the ecosystem attribute(s) they are intended to measure, in a theoretically- or empirically-expected direction.
4. **Responds predictably and is sufficiently sensitive to changes in a specific management action(s) or pressure(s):** Management actions or other human-induced pressures should cause detectable changes in the indicators, in a theoretically- or empirically-expected direction, and it should be possible to distinguish the effects of other factors on the response.
5. **Linkable to scientifically-defined reference points and progress targets:** It should be possible to link indicator values to quantitative or qualitative reference points and target reference points, which imply positive progress toward ecosystem goals.
6. **Complements existing indicators:** This criterion is applicable in the selection of a suite of indicators, performed after the evaluation of individual indicators in a post-hoc analysis. Sets of indicators should be selected to avoid redundancy and increase the complementary of the information provided, and to ensure coverage of Key Attributes.

Data considerations

1. **Concrete:** Indicators should be directly measureable.
2. **Historical data or information available:** Indicators should be supported by existing data to facilitate current status evaluation (relative to historic levels) and interpretation of future trends.
3. **Operationally simple:** The methods for sampling, measuring, processing, and analyzing the indicator data should be technically feasible.
4. **Numerical:** Quantitative measurements are preferred over qualitative, categorical measurements, which in turn are preferred over expert opinions and professional judgments.
5. **Broad spatial coverage:** Ideally, data for each indicator should be available in all PSP Action Areas.
6. **Continuous time series:** Indicators should have been sampled on multiple occasions, preferably without substantial time-gaps between sampling.
7. **Spatial and temporal variation understood:** Diel, seasonal, annual, and decadal variability in the indicators should ideally be understood, as should spatial heterogeneity/patchiness in indicator values.
8. **High signal-to-noise ratio:** It should be possible to estimate measurement and process uncertainty associated with each indicator, and to ensure that variability in indicator values does not prevent detection of significant changes.

Other considerations

1. **Understood by the public and policymakers:** Indicators should be simple to interpret, easy to communicate, and public understanding should be consistent with technical definitions.
2. **History of reporting:** Indicators already perceived by the public and policymakers as reliable and meaningful should be preferred over novel indicators.
3. **Cost-effective:** Sampling, measuring, processing, and analyzing the indicator data should make effective use of limited financial resources.
4. **Anticipatory or leading indicator:** A subset of indicators should signal changes in ecosystem attributes before they occur, and ideally with sufficient lead-time to allow for a management response.
5. **Regionally/nationally/internationally compatible:** Indicators should be comparable to those used in other geographic locations, in order to contextualize ecosystem status and changes in status.

Indicator Evaluation Process

After constructing the framework, the explicit definition of the evaluation criteria, and the selection and organization of the individual indicators, each indicator was evaluated individually. Our intent was to assess each indicator against each evaluation criterion by reviewing peer-reviewed publications and reports. We chose this benchmark because it is consistent with the criterion of peer-review used by other chapters of the Puget Sound Science Update, and it is a criterion that is relatively easy to apply in a consistent fashion. However, we do recognize the value of non-peer reviewed documents as well as the opinion of expert panels. Consequently, where we found such documentation, we include it, while noting that it is not peer-reviewed. The result is a matrix of indicators and criteria that contains specific references and notes in each cell, which summarize the literature support for each indicator against the criteria. We reiterate here that our goal is to review and evaluate indicators that could inform the policy-science process underway in the Puget Sound Partnership. We do not recommend a final indicator portfolio.

Some specific points on the evaluation process:

1. The intent of including references was to provide sufficient evidence that the indicator met (or failed to meet) each of the specific evaluation criteria. Based on the references, an independent evaluator should be able to understand the important points of the process.
2. As is the standard for the entire PSSU, we required references to be peer-reviewed publications or reports. Internal agency documents were included when it was clear that there had been an explicit peer-review process.
3. There was a preference for literature based on studies conducted in the Puget Sound region.
4. The evaluation notes were meant to be of sufficient detail to allow an independent evaluator to understand the basis for conclusion, when it was not otherwise obvious from the references.
5. Each of the indicators was evaluated against a specific Key Attribute, which they were meant to describe. If, however, the detailed evaluation indicated that the indicator better

described a different Key Attribute, then the individual reviewing that indicator was given the liberty to reassign the indicator.

6. In some instances no references were found relating an indicator to a specific criterion. These cells were left blank.
7. Some of the Data Considerations were evaluated by a simple yes/no response when the conclusion was obvious (e.g., concrete, historical data, operationally simple, numerical, spatial coverage, continuous).

Certain criteria proved to be problematic during the evaluation. These included:

1. **Relevant to Management Concerns.** It was not always obvious to a reviewer if a particular indicator was relevant to management concerns. Management concerns were not always clearly documented or lacked specificity. Often, PSP background documents were referenced based on the presumption that they accurately reflected management concerns.
2. **Understood by Public and Policy Makers.** There is a lack of literature documenting the degree to which citizens or their representatives understand the meaning or intent of specific ecosystem indicators (or ecological concepts). The evaluation of an indicator under this criterion is often presumptive and may vary depending on the reviewer.
3. **Cost Effective.** The value of the information from an indicator was difficult to determine. Cost effectiveness may be measured by the value of decisions made based on the new information from the indicator. This is difficult because not only are decision scenarios complex and difficult to evaluate on a cost basis, but it is also difficult to predict the range of potential decisions that could be made based on the new information. Further, cost effectiveness may be measured by the opportunity cost of choosing one indicator over another. Assuming that the suite of indicators (and information) is limited, the value of choosing one indicator over another is not only related to the new information gained, but also the cost of the information lost by not collecting data for other indicators.
4. **Complements Existing Indicators.** It was necessary to have a complete suite of indicators in order to evaluate the complementarity and/or redundancy of each of the indicators. As mentioned above, this criterion should be applied in a post-hoc analysis.

Key point: Indicators should be evaluated using widely accepted and transparent criteria. This chapter used criteria derived from the vast literature on ecosystem indicators, which were divided into three groups: 1) Primary considerations are essential criteria that should be fulfilled by an indicator; 2) Data considerations relate to the actual measurement of the indicator; 3) Other considerations criteria may be important but not essential for indicator performance.

Next Step: Evaluations were focused on the presence or absence of peer-reviewed evidence that an indicator met each criterion. Thus, we did not evaluate the rigor of the evidence. An important next step will be to carefully review the evidence and distinguish between weak and strong evidence.

Results of the Indicator Evaluations

Detailed spreadsheets showing the results of the indicator evaluation are available at the following link: Indicator Spreadsheets. Summary tables are included at the end of this section. Following the framework outlined in Section 3, we organize the results of the evaluation by PSP ecosystem goals (i.e. Species, Habitat, Food Webs, Water Quality, and Water Quantity). Each goal has been divided per unique ecosystem domain (marine, freshwater, interface, and terrestrial).

A focused discussion of the evaluation by goal is presented in the following sections. The discussions include a summary of the results of the evaluation, as well as a presentation of the salient issues to Puget Sound, which were identified during the literature review. The section on Water Quality includes the complete literature review, which was performed in order to identify indicators appropriate for use in Puget Sound.

1. Species Evaluation

This version of the Puget Sound Science Update provides an initial evaluation of species indicators, but is not intended to be comprehensive. Focal species identified by O'Neill et al. [34] were evaluated as either measures of population size or population condition. Many of these were identified as potentially good species indicators, and several may be relevant to key attributes of the other PSP goals (e.g., habitat condition).

- The inclusion of more candidate freshwater and interface indicators, as well as indicators for population condition of marine and terrestrial species
- Evaluation of population condition indicators other than those related to organism condition (e.g., age structure, population structure)
- Explicitly defining vague indicators (e.g., insect species)||

Commonly used data sources to evaluate species indicators included: Washington Departments of Ecology, Fish and Wildlife, and Natural Resources, NMFS, USFWS and USGS.

Indicators of population size

We focused on three metrics of population size: the number of individuals in a population, total biomass, and population dynamics. Population abundance and biomass data are key measures of the overall health of a focal species. Insight into the status and trends of a focal species can also be used to infer changes in ecosystem structure and function. While population size can be used to assess population viability, more accurate predictions of viability can be obtained by including the mechanisms responsible for the dynamics of the population. Population dynamics thus provide a predictive framework to evaluate the combined effect of multiple mechanisms of population regulation (e.g., birth and death rates, immigration and emigration) to evaluate changes in abundance through time. The Washington Departments of Ecology, Fish and Wildlife, and Natural Resources, USGS, and NMFS, among others, have ongoing monitoring efforts of population status and trends for numerous species throughout the sound.

The use of species attributes by the PSP has largely been limited to population size. For example, in the 2007 and 2009 State of the Sound documents only measures of population size were reported for all species indicators (except salmon) [40, 116]. While the PSP has historically recognized the importance of monitoring species health or condition, their use of 'condition' was limited to measurements of toxic contaminants in various species, and was meant to be an indicator of Water Quality (see [40, 116]). In the following section we discuss the utility of population condition as an independent attribute for assessing the status of focal species in Puget Sound.

Indicators of population condition

Whereas the preceding attribute is concerned with measures of population size, there are instances when the "health" of the population may be of interest. For example, monitoring changes in population condition may presage an effect on population size or provide insight into long-term population viability. The dynamics of many populations are better understood through knowledge of population condition such as organism condition, age structure, genetic diversity, phenotypic diversity, and population structure. Impaired condition of any or all of these subcategories indicates biological resources at risk.

Organism condition represents both physiological and disease status. Physiological status reflects the general condition of an organism whereas disease status signals the presence of harmful agents. Thus monitoring changes in organism condition can be used to infer changes in environmental conditions. Population age structure is used to evaluate long-term stability and viability of a population by modeling trends through time. Genetic diversity measures are important in assessing population condition because loss of genetic variation can reduce individual fitness as well as the ability of populations to evolve in the future [62]. Phenotypically diverse populations (i.e., each subset of the total population is adapted to a slightly different environmental condition) have an increased capacity for adapting to changing environmental conditions, which can be vital for long-term population sustainability. Similarly, insight into population structure (i.e., how different populations interact in space) can be useful for predicting the effects of changing conditions on population viability. WDFW and NMFS monitoring programs (among others) provide important information for assessing population conditions.

Evaluation of species indicators in Puget Sound

There were seventy-seven species indicators identified by O'Neill et al. [34]and of these, we have evaluated sixty. The majority of those evaluated are indicators of population size for marine and terrestrial species. Several focal components would benefit from indicator development including Interface Species (population size and condition), Freshwater Species (population size and condition), and Terrestrial Species (population condition only). The current status of indicator evaluations for each species focal component is summarized below.

Marine species indicator evaluation

Population size. There were twenty-nine indicators of marine species population size identified (Table 4). Most of these indicators are conceptually valid, and about half those evaluated were an overall good indicator of species abundance. There were several good indicators relevant to food webs as well as key attributes for other PSP goals (e.g., habitat condition). Valuable data sources for assessing marine species abundance included (among others) WDFW, WDOE, WDNR, USGS and USFWS, and NMFS.

In general, indicators that did not perform well failed because:

- Data are unpublished, poorly documented or does not exist
- Unable to assess whether they respond predictably to ecosystem attributes or to management actions or pressures
- Variation is not well understood, especially for migratory species

Indicators that performed well against all criteria included: total run size of salmonids (hatchery and wild), salmon and steelhead status and trends, marine bird aerial estimates (non-breeding populations), and pinto abalone status and trends. Pinto abalone is a unique indicator because, while it performs well against most criteria, is not necessarily theoretically-sound. A study by Rothaus et al. (2008) concluded that declines in abalone abundance are not likely to recover due to historic overharvesting, making it a poor indicator for healthy and sustaining species [117].

Table 4. Summary of Marine Species - Population Size indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Pinto abalone status & trends has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Southern Resident killer whale population trends	3	4	3	Overall good indicator of species (e.g., vital sign) but may not be best indicator of ecosystem structure & function. Also, does not respond predictably to management actions.
	Gray whale status & trends	3	3	0	May serve as a good indicator of species abundance. Difficult to determine impacts of management actions b/c long-lived and migratory. Gray whales may be an indicator for climate change if migratory patterns shift.
	Harbor porpoise/Dall's porpoise status & trends	0	2	1	No evidence to recommend this as an indicator. Few studies have looked at abundances in Puget Sound, they are highly migratory, and very little information is known about populations.
	Harbor seal status & trends	3	8	3	Overall good indicator of species abundance (e.g., vital sign), but not necessarily food webs. To avoid redundancy, choose between this indicator and harbor seal – food web interaction.
Key Fish	Total run size of salmonids (hatchery & wild)	5	8	4	Overall good indicator; peer-reviewed literature supporting most criteria.
	Harvest of wild salmonid populations	Not yet evaluated			
	Exploitation rates of wild salmonid populations	Not yet evaluated			
	Marine bottomfish harvest	2	3	3	Theoretically-sound however, unable to determine response to ecosystem attributes or management actions/pressures. MSY estimates lacking for many marine bottomfish in PS.
	Rockfish status & trends	1	3	1	Rockfish notes as best indicator for some ecosystem attributes [118], but due to life history characteristics, it is difficult to assess whether they respond predictably to ecosystem attributes or management. Historical harvest data available.
	Salmon & steelhead status & trends	5	8	4	Overall good indicator; peer-reviewed literature supporting most criteria.
	Marine resident fish species status & trends	0	0	0	Information does not exist for several of the species suggested. Rationale for collecting these data needs to be further evaluated prior to developing this indicator.
Birds	Marine waterfowl harvest	0	0	1	Theoretically-unsound. Mostly unpublished data; marine waterfowl population numbers are not well documented, so difficult to determine the effects of harvest on overall abundances.
	Marine bird aerial estimates – non-breeding populations	3	8	4	Overall good indicator of species abundance (no relevance to food webs). Long history of reporting that covers virtually all PSP action areas. Because a mix of residents and migrants, changes in abundance could be the result of pressures outside PS.
	PIGU nesting colony trends	0	0	0	Poor indicator. Difficult to find any peer-reviewed literature on pigeon guillemot population numbers or nesting colony trends.
	Marine bird breeding abundance	1	0	0	Poor indicator. There are Canadian seabird breeding datasets; equivalent datasets lacking for Puget Sound.
	Black oystercatcher abundance	4	3	2	Good theoretical species indicator however, patchy surveys of varying levels of sampling effort, coverage, and methodologies preclude formal comparison of data. Also, not present in southern and central Puget Sound.
	Marine bird fishing mortality	3	2	0	Theoretically-sound and relevant, but scattered reporting of bycatch in local fisheries. Complicated data analysis.
	Glaucous wing gull abundance at nesting colonies	1	4	2	Theoretically-sound but does not meet any other Primary Considerations. Data available, mostly for north Puget Sound. Not particularly cost-effective and in general, not locally appreciated.
	Marine birds – shore-based estimates of non-breeding populations	Not yet evaluated			
	Western sandpiper status & trends	2	3	2	Good species indicator and may also be a good indicator of habitat condition. Habitat loss is identified as main pressure, but difficult to ascertain what the impact has been on population abundance. Trend analysis of data is absent.
	Scoter & Harlequin ducks – non-breeding populations	3	3	1	May be a good indicator of species and food webs b/c they follow herring spawning. Unpublished data sets that are regionally patchy; variation in local trends not well understood.
	Cormorant abundance at nesting colonies	2	6	2	May be a good species and food web indicator; Slater & Byrd (2009) found bird abundance to predict changes in marine food webs [119]. Long-term monitoring programs so good data availability.
Shellfish & Other Inverts	Dungeness crab abundance	1	2	2	Theoretically-sound but does not meet any other Primary Considerations. Abundance is measurable through pre- and post-season crab pot surveys but no published data available.
	Dungeness crab harvest	2	6	4	May be a good indicator b/c theoretically-sound and relevant to management, but year-to-year variation in harvest is not well-understood. Long-term data available from harvest report cards.
	Pinto abalone status & trends	3	6	4	Long-term data available and relevant to management, but Rothaus et al. (2008) concludes that declines in abundance are not likely to recover due to historic overharvesting [117].
Plants	Eelgrass status & trends	Evaluated under Marine Habitats			
	Kelp status & trends	Evaluated under Marine Habitats			
	Marine macro algae status & trends	Evaluated under Marine Habitats			

Population condition. There were fifteen indicators of population condition (Table 5). Most indicators were based on measures of organism condition, with considerably fewer indicators representing the other measures of population condition (i.e., age structure, population structure, phenotypic diversity, and genetic diversity). In the future, candidate indicators may need to be developed for these additional measures of population condition, especially as they relate to focal species of management concern.'"

Many of the indicators of organism condition (e.g., toxics in mussels) listed were evaluated under Marine Water Quality; we decided that for the purposes of this document, contaminant-related indicators in lower trophic level organisms provided pertinent information on water condition. Future iterations of the PSSU may choose to evaluate such indicators in relation to species condition, especially as the science develops to support the idea of population-level effects [120]. The remaining four indicators evaluated under marine species population condition were theoretically-sound, and all but one (marine bird mortality) performed well against all criteria. These included: toxics in harbor seals, liver disease in English sole, and toxics in adult Chinook and coho salmon. Data sources mainly used to evaluate organism condition included WDFW, NMFS, Cascadia Research, Fisheries and Oceans Canada, and past PSAT reports. Several indicators including smolt to adult return for wild salmonids, salmonid diversity, star protein/DNA damage in fish, abnormal fish embryonic development, marine growth and survival of juvenile coho, and salmonid population spatial structure still need to be evaluated.

Table 5. Summary of Marine Species - Population Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Marine bird mortality has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Toxics in harbor seals	4	7	3	Good indicator but more sites are needed for Puget Sound.
Key Fish	Smolt to adult return for wild salmonids	Not yet evaluated			
	Salmonid diversity	Not yet evaluated			
	Liver disease in English sole – see also Marine Water Quality	5	8	5	Populations with elevated liver disease show symptoms of reproductive impairment and age-selected mortality. Changes in prevalence of liver disease are used to document improvements in fish health. Thresholds for PAH levels in sediment associated with increased prevalence have been defined. There is historic coverage of over 50 sites, currently limited to 8 with representing urban, near-urban and non-urban site.
	Vtg induction in male fish	Evaluated under Marine Water Quality			
	Star protein/DNA damage	Not yet evaluated			
	Abnormal embryonic development	Not yet evaluated			
	Toxics in adult Chinook & coho salmon – see also Marine Water Quality	3	7	4	May be a good overall indicator of species condition (e.g., vital sign indicator), but does not respond predictably to management actions or pressures. Long-term monitoring program for Chinook salmon was discontinued in 2006. Risk to fish health will go down with lower contaminant levels.
	Toxics in adult Pacific herring – see also Marine Water Quality				Impairment to fish health increase with toxic levels in fish. Thresholds for toxics have been defined adult herring. Sampling requires technical expertise and equipment. Historic coverage major herring populations. Continuous time series for three populations from 1999.
	Marine growth & survival of juvenile Coho	Not yet evaluated			
	Salmonid population spatial structure	Not yet evaluated			
	Toxics in English sole – see also Marine Water Quality				Elevated contaminant levels in English sole (including PAH metabolites in bile) increase with concentrations in the environment and elevated levels are associate with liver disease and reproductive impairment. Thresholds exist for some chemicals. Sampling requires specialized techniques and instrumentation. Historic coverage of over 50 sites, currently limited to 8 sites representing urban, near-urban and non-urban.
Birds	Marine bird mortality	2	8	2	Data has been collected all over Puget Sound since 2000. Theoretically-sound and responds to management efforts to reduce seabird bycatch. Underappreciated by management and the public b/c lower number of dead birds generally found in the sound.
Shellfish & Other Inverts	Benthic infaunal community structure (sediment quality)	Evaluated under Marine Water Quality			
	Toxics in mussels – see also Marine Water Quality				Threshold specific to the health of mussels are not know. Continuous coverage from mid 80's.

Freshwater species indicator evaluation

Population size. There were five indicators of freshwater species population size identified (Table 6). Of these, three have not been evaluated (mammal species, total number of spawning adult salmonids, and freshwater resident fish species). The remaining indicators, waterfowl status and trends of midwinter populations and waterfowl breeding surveys, both performed poorly. WDFW, USFWS, and the Pacific Flyway Council provide overviews of waterfowl population status and trends in the Pacific flyway region, however there are no specific references to Washington populations.

Also of note, mammal species and freshwater resident fish species may need to be more explicitly defined before they are evaluated.

Table 6. Summary of Freshwater Species - Population Size indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Waterfowl breeding surveys has peer-reviewed literature supporting 0 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Mammal species	Not yet evaluated			
Key Fish	Total number of spawning adult salmonids (hatchery & wild)	Not yet evaluated			
	Freshwater resident fish species	Not yet evaluated			
Birds	Waterfowl status & trends of midwinter populations	0	0	0	Currently a poor indicator; references provided by WDFW and USFWS provide an overview of waterfowl population status & trends, but no specific references for WA midwinter populations. More specific information is needed.
	Waterfowl breeding surveys	0	0	0	Currently a poor indicator; references provided by WDFW and USFWS provide an overview of waterfowl population status & trends, but no specific references for WA breeding surveys. More specific information is needed.

Population condition. Six indicators of freshwater species population condition were identified (Table 7), and only one indicator (salmonid population growth rate) has currently been evaluated in this section; it received an overall good rating across all the criteria with references primarily from NMFS. Three indicators, toxics in juvenile salmon, benthic IBI and aquatic vertebrate IBI, are evaluated under Water Quality though they do pertain to population condition as well. Two remaining indicators, recruits per spawner of wild salmonids and egg to smolt survival of wild salmonids, need to be evaluated.

Table 7. Summary of Freshwater Species - Population Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Salmonid population growth rate has peer-reviewed literature supporting 5 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Key Fish	Recruits/spawner of wild salmonids	Not yet evaluated			
	Egg to smolt survival of wild salmonids	Not yet evaluated			
	Salmonid population growth rate	5	8	4	Overall good indicator; peer-reviewed literature supporting most criteria.
	Toxics in juvenile salmon – see also Interface Water Quality				Chinook salmon is an ESA listed species in Puget Sound. Age of the fish will determine whether local or regional water quality is reflected. Health-effects thresholds exist for PCBs and TBT. No consistent monitoring program in Puget Sound, however, multiple studies provide baseline data.
Shellfish & Other Inverts	Benthic IBI – macro-invert communities	Evaluated under Freshwater Quality			
Key Species	Aquatic vertebrate IBI	Evaluated under Freshwater Quality			

Terrestrial species indicator evaluation

Population size. There were nineteen indicators of terrestrial species population size identified (Table 8). Twelve of these indicators are conceptually valid, and about half may be good overall indicators of species abundance. Several indicators may provide relevant information to key attributes for other PSP goals (e.g., habitat area and condition). Data from WDFW and USGS Breeding Bird Survey (BBS) provided nearly all of the information on terrestrial species abundance. The residual indicators generally performed poorly because:

- Data coverage is limited
- Unable to determine relevance to management or response to management actions or pressures
- Tracking or monitoring species abundance is particularly difficult

Indicators that performed relatively well against all criteria included: terrestrial game species harvest, terrestrial breeding bird counts, terrestrial bird species, and Christmas bird counts. Several indicators including deer population status and trends, elk status and trends, backyard wildlife population trends, bald eagle status and trends, cavity nesting birds, Taylor's checkerspot butterfly, and marbled murrelets also performed relatively well against the primary considerations, but failed most of the data and other considerations criteria.

The majority of indicators that did well against the criteria are either mammals or birds, and it may be useful to develop candidate indicators for underrepresented or absent guilds (e.g., insects, plants).

Table 8. Summary of Terrestrial Species - Population Size indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Upland plant

species has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Mountain goat status & trends	0	0	0	Poor indicator due to the inherent difficulties in tracking them.
	Deer population status & trends	3	3	4	Theoretically-sound and relevant to management. Population estimates are derived from harvest statistics (WDFW). Good species indicator and may also provide information on food webs and habitat condition since ungulate abundance can significantly affect ecosystem structure and function through browsing pressure.
	Elk status & trends	3	3	4	Theoretically-sound and relevant to management. Population estimates are derived from harvest statistics (WDFW). Good species indicator and may also provide information on food webs and habitat condition since ungulate abundance can significantly affect ecosystem structure and function through browsing pressure.
	Backyard wildlife population trends	3	1	1	May be a good species indicator, although evidence for management relevance is lacking (but may be used to encourage) citizen action). Monitoring data sources are likely to be widely dispersed and patchy in time.
	Terrestrial game species harvest	3	7	4	Overall good indicator; peer-reviewed references support many of the criteria.
	Mammal species	0	0	1	Currently a poor indicator b/c compilation of species where some are more extensively monitored than others. Possibly link this indicator with issues of landscape connectivity (of particular importance to mammals) to evaluate progress of landscape planning and assessment strategies.
Birds	Terrestrial breeding bird counts	3	6	4	Theoretically-sound and long-term data available. Difficult to determine management relevance or response to management actions/pressures. Phenological timing of migrations may serve as a useful leading indicator of climate change impacts.
	Peregrine falcon nesting surveys	3	3	4	Does not appear to be a good indicator (theoretically-unsound); lack of data in Puget Sound and variations in abundance not well understood.
	Bald eagle status & trends	5	3	2	Overall good species indicator (e.g., vital sign) although data coverage and variability not well documented in Puget Sound.
	Band-tailed pigeon mineral site counts	0	3	0	Appears to be a poor indicator. Linked to rare habitat type (mineral sites), but is described as being common in the region. Impacted by significant ecosystem changes from anthropogenic causes however, other indicators highlight impacts more distinctly.
	Christmas bird counts	3	6	4	May be a good indicator although data coverage in Puget Sound is limited. Also, evidence that indicator responds to management actions or pressures is lacking.
	Marbled murrelet presence at occupied sites	4	0	0	Overall good theoretical indicator. WDFW has monitored abundance, but apparent reliance on at-sea monitoring has made them harder to track. Threatened species with sensitivity to habitat fragmentation, a particular development concern in Puget Sound.
	Great blue heron	0	3	1	Do not have enough peer-reviewed evidence to support their use as an indicator. However, sensitive to development disturbance so may be useful in assessing landscape changes.
	Cavity nesting birds status & trends	4	4	1	Overall good indicator; reflect important functional guild and indicate significant land cover change impacts on species. Historical data trends lacking.
	Terrestrial bird species	3	6	4	May be good indicator but link to management is missing. Good data availability; migration timing may serve as leading indicator of climate change impacts.
Insects	Taylor's checkerspot butterfly status & trends	3	4	0	May be a good indicator although difficult to attribute population declines to human pressures (thought to be due to habitat loss). Not much good data available (appears mostly anecdotal).
	Insect species	Not yet evaluated			
Plants	Upland plant species	2	0	2	Theoretically-sound and responds to ecosystem attributes; data coverage is limited. Good indicator of species with relevance to ecosystem structure and function; may be anticipatory indicator through shifts in phenology.
	Terrestrial plant species status & trends	0	0	0	Poor indicator. Upland plant species is more targeted and more relevant.

Population condition. One indicator (Avian flu) has been identified for this attribute but has yet to be evaluated (Table 9). New indicators that characterize population condition of focal species should be developed for this section.

Table 9. Summary of Terrestrial Species - Population Condition indicator evaluations.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Birds	Avian flu	Not yet evaluated			

Interface species indicator evaluation

Population size. There were two indicators identified for interface species population size (Table 10). These indicators, stillwater breeding amphibians and amphibian and reptile species, have yet to be evaluated. Additional indicators that assess population abundance of focal species should be developed for this section.

Table 10. Summary of Interface Species - Population size indicator evaluation.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Amphibians & Reptiles	Stillwater breeding amphibians	Not yet evaluated			
	Amphibian & reptile species	Not yet evaluated			

Population condition. No indicators have been identified for interface species population condition. Candidate indicators may need to be developed for interface focal species population condition.

Food Web Evaluation

This version of the Puget Sound Science Update provides an initial evaluation of food web indicators, but is not intended to be comprehensive. Highlights include the evaluation of individual species or species complexes as food web indicators due to their key functional roles (e.g., forage fish, jellyfish), and the identification of existing data sources for assessing food web structure and function at Washington State agencies and via satellite.

Next Step: Future versions of this document would benefit from the evaluation of more indicators pertinent to the Freshwater and Terrestrial Domains, and the inclusion of more candidate indicators in the Marine Domain to ensure a full treatment of the key attributes identified in Section 3.2.3.3. Indicators of energy and material flows deserve particular attention in future assessments, as they were not the focus of the review by O'Neill et al. [34].

Key Point: Because of the difficulty of directly measuring attributes of food web health, ecosystem models have the potential to greatly contribute to the evaluation of foodweb indicators [118]. We encourage the development of ecosystem models as a tool for testing the performance of food web indicators.

Indicators of community composition

Species abundance and biomass data can be used to paint a synthetic picture of community composition, especially when viewed collectively with respect to particular Domains and in relation to species' trophic and functional roles. Even in isolation, insight into the status and trends of keystone species (i.e., those that have a disproportionate influence on food web structure relative to their abundance), highly connected species (i.e., those that are consumers of and consumed by many other species), minimally connected species, and those species representing a large proportion of the biomass in Puget Sound can be useful for interpreting the structural configuration of the food web [47]. In addition, species abundance and biomass data can be summarized into index values that describe the three different types of diversity defined in Section 3.2.3.3 (species, trophic, and response diversity). Dietary composition data, especially for higher trophic level predators such as marine mammals and birds, offer an alternative inroad to understanding community composition in Puget Sound and are available for a limited subset of species. Ongoing monitoring programs led by the Washington Departments of Ecology, Fish and Wildlife, and Natural Resources, among others, provide a rich source of information on community composition in Puget Sound. The challenge is to sort through these data to extract meaningful summary descriptions.

Indicators of energy and material flows

Proxies for primary productivity such as chlorophyll a concentration and phytoplankton biomass (in the Marine Domain) and leaf area index (in the Terrestrial Domain) are the most widely available indicators for energy and material flows in Puget Sound. Remote-sensing data are a valuable source of this information, though other, labor-intensive approaches are available for obtaining spatially explicit and finely resolved understanding of primary productivity as well (e.g., plankton tows, forest inventories, etc.). Alternatives to remote-sensing data are especially important in the Marine Domain, where it is difficult to obtain reliable estimates of primary productivity in nearshore areas at small spatial scales. More detailed data collection or modeling efforts (e.g., Ecopath with Ecosim) are needed to estimate the magnitude of secondary production and pathways of energy flows throughout the food web. Biogeochemical approaches for measuring cycling rates are well developed, especially with respect to inorganic nutrients, but such data are not widely available and can be quite expensive to obtain. Making up for this deficiency will require detailed, broad-scale studies of how different species interact with the physical and chemical oceanography of Puget Sound to affect processes such as nitrogen fixation, carbon sequestration, and microbial decomposition.

Evaluation of food web indicators in Puget Sound

There were nineteen Food Web indicators identified and of these, we have evaluated fifteen. The degree to which food web indicators satisfy our evaluation criteria is highly variable, and about half of them did not perform well against any of the criteria. The majority of evaluated indicators were from the Marine Domain, and no indicators have yet been evaluated for Freshwater Food Webs. The current status of indicator evaluations for the Food Webs Goal is summarized below.

Marine food web indicator evaluation

Eleven indicators of Marine Food Web community composition and two indicators of Marine Food Web Energy and Material Flows were evaluated (Table 11 and Table 12). The status and trends of benthic and pelagic fish communities species, marine shorebird diets, and jellyfish abundance performed best against the primary considerations for indicators of community composition. Of these indicators, however, only marine shorebird diets also met a majority of the Data and Other Considerations criteria. The general deficiency of quantitative data suggests the potential utility of several indicators while highlighting the need to begin data collection and monitoring. Most of the community composition indicators that did not perform well against the Primary Considerations also were deficient under the Data Considerations criteria. One of the biggest challenges for developing Marine Food Web indicators will be to increase their specificity prior to evaluation; several indicators, like the marine biodiversity index, shellfish, and benthic macroinvertebrates, were considered too vague to evaluate properly.

Phytoplankton biomass and chlorophyll a concentration provide similar information about primary productivity in the Puget Sound Marine Food Web. Both indicators performed well against the Primary Considerations for indicators of energy and material flows. However, chlorophyll a concentration met more of the Data and Other Considerations. Due to this indicator's reliance on remotely sensed data, however, it is unlikely to provide information about energy and material flows on spatial scales smaller than the PSP Action Areas. We suggest the evaluation of additional indicators of energy and material flows in the future.

Table 11. Summary of Marine Food Webs – Community Composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Macro benthic inverts has peer-reviewed literature supporting 0 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Mammals	Harbor seals – food web interaction	1	5	2	Should be a good indicator of fish community composition, and possibly of population condition. Breadth of seal diet may limit power to detect small changes. Spotty historical data available throughout the region.
Key Fish	Benthic fish species status & trends	4	3	0	Overall appear to be good indicators of food web community composition, although historical data is currently lacking making it difficult to determine long-term trends.
	Bentho-pelagic fish status & trends	4	2	0	Overall appear to be good indicators of food web community composition, although historical data is currently lacking making it difficult to determine long-term trends.
	Bottomfish species (rats & flats) status & trends	1	0	4	Bottomfish noted as best indicator for some ecosystem attributes [118], although only appears as adequate indicator using our criteria. Difficult to determine if this indicator responds predictably to ecosystem attribute or actions/pressures. Patchy historical data.
Birds	Marine shore birds – food web interaction	3	7	2	Overall a good indicator, with relevance to forage fish prey species (diet variability responds to prey variability). Historical data available, although limited to two PSP action areas.
Shellfish & Other Inverts	Jellyfish	4	3	2	Theoretically-sound – jellyfish should be reliable indicators of trophic energy transfer & community composition. Responds predictably to actions and pressures, and may be especially relevant to understanding the status of forage fish. Historical data is limited, although still a promising indicator.
	Shellfish	0	0	0	Currently unable to properly evaluate because indicator is too vague. Recommend selection of particular species of bivalves as indicators.
	Macro benthic inverts	0	0	0	Currently unable to properly evaluate because indicator is too vague. Recommend selection of particular species of benthic inverts as indicators.
Key Species	Marine biodiversity index	0	0	0	Currently there is not sufficient information available to evaluate this indicator; the WA Biodiversity Council has planned to develop this indicator further.
	Marine fish/invert status & trends in marine reserves	0	0	0	Consolidate this indicator with 'marine fish/invert status & trends at rocky habitats'. If monitored inside marine reserve, it should also be monitored outside reserve to serve as a reference point.
	Marine fish/invert status & trends at rocky habitats	1	4	0	Difficult to evaluate as currently defined; need to explicitly define species or community parameters of interest. Some historical data available.

Table 12. Summary of Marine Food Webs – Energy and Material Flow indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example,

Chlorophyll a has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Plants	Phytoplankton biomass	3	1	1	Good indicator of pelagic ecosystems, especially nutrient cycling and the amount of primary production. Only limited amounts of historical data available. Provides similar information as chl a so choose one to avoid redundancy.
	Chlorophyll a	3	7	2	Chl a is a good proxy for overall primary productivity and nutrient cycling/uptake. Good historical data available. Phytoplankton biomass provides similar information to chl a concentration so choose one to avoid redundancy.

Freshwater food web indicator evaluation

Three indicators of Freshwater Food Web community composition were identified (Table 13), but unfortunately none were evaluated for this version of the PSSU. No indicators of Freshwater Food Web energy and material flows appear on the list of candidates suggested by O'Neill et al. [34]. Indicators of this Focal Component clearly deserve greater attention in future evaluation processes.

Table 13. Summary of Freshwater Food Webs – Community Composition indicator evaluations.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Key Fish	Freshwater fish biomass/stream length	Not yet evaluated			
Shellfish & Other Inverts	Macro invert assemblages – observed/expected	Not yet evaluated			
Key Species	Freshwater biodiversity index	Not yet evaluated			

Terrestrial food web indicator evaluation

O'Neill et al. identified one indicator of Terrestrial Food Web community composition (Table 14), the terrestrial biodiversity index [34]. Unfortunately, because it is still in development, this indicator did not meet many of the evaluation criteria under the Primary, Data, and Other Considerations. No indicators of Terrestrial Food Web energy and material flows were proposed by O'Neill et al. [34] and none were evaluated. As with Freshwater Food Webs, indicators of Terrestrial Food Webs clearly deserve greater attention in future evaluation processes.

Table 14. Summary of Terrestrial Food Webs – Community Composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Terrestrial biodiversity index has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria.

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Key Species	Terrestrial biodiversity index	2	1	1	Fairly recent indicator developed by the WA Biodiversity Indicators Project. May be a good indicator for management, but more vetting required before fully usable for biodiversity assessment.

Interface food web indicator evaluation

Two related indicators of Interface Food Web community composition were identified by O'Neill et al. [34] (Table 15): forage fish and herring status and trends. Both indicators performed well against the Primary Considerations, though many of the Data and Other Considerations were not met. No indicators of Interface Food Web energy and material flows were proposed by O'Neill et al. [34] and none were evaluated. In general, new, additional indicators of this Focal Component should be evaluated in the future.

Table 15. Summary of Interface Food Webs – Community Composition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Forage fish status & trends has peer-reviewed literature supporting 4 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Guild	Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Key Fish	Forage fish status & trends	4	1	0	Theoretically-sound and relevant, but difficult to determine whether forage fish populations are responding to management actions or pressures or environmental conditions. Highly sensitive to uncontrollable environmental conditions.
	Pacific herring status & trends	4	1	0	Theoretically-sound and relevant, but difficult to determine whether forage fish populations are responding to management actions or pressures or environmental conditions. Highly sensitive to uncontrollable environmental conditions. Good data for many Puget Sound stocks.

Habitat Evaluation

This version of the Puget Sound Science Update provides an initial evaluation of habitat indicators, but is not intended to be comprehensive. Highlights include evaluation of marine and interface habitats (area and condition), as well as evaluation of a number of indicators of freshwater and terrestrial habitats condition. Many measures of habitat condition, especially those relating to water quality, were addressed under the PSP Water Quality goal.

- The inclusion of more candidate indicators for habitat area and pattern/structure (of all domains)
- Evaluation of habitat area and pattern/structure indicators for freshwater and terrestrial habitats
- Evaluation of freshwater habitats condition indicators
- Defining or identifying ‘priority habitats’ for priority habitats condition indicator (which appears under marine, freshwater, and terrestrial domains)

Commonly used data sources to evaluate habitat indicators included: Washington Departments of Ecology, Fish and Wildlife, and Natural Resources, and the Washington Biodiversity Council.

Indicators of habitat area and pattern/structure

Habitat area and pattern/structure are key measures of the overall health of a system, especially when they represent priority habitats. Insight into the status and trends of priority habitats area or pattern/structure can be used to infer changes in the status and trends of biota as well as abiotic processes. For example, changes in habitat area or pattern/structure can influence the amount of water runoff or coastal flooding, as well as regional species persistence. Thus insight into the status and trends of habitat area and pattern/structure can be useful for interpreting changes in ecosystem structure, function and processes.

Habitat area reflects the areal extent of a habitat as well as its shape, and can influence local population persistence and size for a single species [121]. While habitat area is important for maintaining biota, pattern/structure measures (e.g., the number of patches of each habitat, fractal dimension, and connectivity) also plays a significant role. The number of patches of each habitat (i.e., patch richness) may be correlated with species richness, thus monitoring patch number may be used to interpret trends in species biodiversity. Fractal dimension provides a measure of habitat complexity; natural areas tend to be more complex compared with human-altered areas, leading to changes in species richness [122, 123]. Connectivity between habitat patches affects the ability of an organism to cross between patches, and can be important for regional population abundance and survival [121]. WDNR monitoring programs, among others, provide an abundant source of information on habitat area in Puget Sound.

Indicators of habitat condition

Whereas the preceding attribute is concerned with measures of habitat area and pattern, it is also important to assess habitat quality or condition. Habitat condition reflects the basic needs of a species (e.g., food, water, cover) and is a critical component to predict species distributions [42] and population abundance and survival [121]. For example, important variables for fish habitat would include water quality parameters (e.g., DO levels, temperature) as well as the presence and abundance of non-native invasive species or nuisance species that compete for resources. Thus, habitat condition refers to abiotic (i.e., physical and chemical properties) and biotic properties (e.g., invasive or nuisance species, dominant species), as well as dynamic structural characteristics.

Abiotic properties (e.g., water and benthic quality parameters) are the most widely available indicators for habitat condition in Puget Sound. However, according to the PSSU framework, they fall under the Water Quality goal and will therefore be discussed in that section. Biotic properties, such as the status and trends of harmful algal blooms or the presence of nuisance species, are a key measure of habitat health and can be used to interpret changes in native species abundance, distribution, and survival. Dynamic structural characteristics cause changes in physical habitat complexity and morphology, and are included in habitat condition because they maintain (or eliminate) the diversity of natural habitats. Data collection led by WDNR, WDFW, and the Washington Biodiversity Council provides important information on habitat condition in Puget Sound.

Evaluation of habitat indicators in Puget Sound

There were sixty habitat indicators identified by O'Neill et al. [34] and of these, we have evaluated thirty-seven. The majority of those evaluated are indicators of area and condition for marine and interface habitats. A small subset of indicators has been evaluated for Freshwater and Terrestrial Habitats, and future versions of this document should focus on completing these evaluations. The current status of indicator evaluations for each habitat focal component is summarized below.

Marine habitat indicator evaluation

Area and Pattern/Structure. Three indicators of marine habitat area were identified (Table 16). Of these, two (eelgrass status and trends and kelp status and trends) were evaluated and performed adequately against the criteria. Both indicators were theoretically-sound, but do not respond predictably to management actions or pressures. In particular, it is difficult to determine causes of variation in habitat area (e.g., natural vs. anthropogenic impacts). Ongoing monitoring programs led by WDNR and the Pacific Northwest National Laboratory, among others, provided extensive information for these indicator evaluations.

Table 16. Summary of Marine Habitats – Area and Pattern/Structure indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Eelgrass status & trends has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Eelgrass status & trends	2	4	2	Theoretically-sound but difficult to determine what causes changes in abundance (natural vs. anthropogenic).
Kelp status & trends	2	5	3	Theoretically-sound but response is limited to floating kelp. Difficult to determine causes of variation in abundance (especially indirect impacts).
Marine macro algae	Not yet evaluated			

Habitat Condition. There were seventeen indicators of marine habitat condition identified (Table 17). The majority of those listed refer to biotic properties (e.g., non-native invasive aquatic species); considerably fewer relate to abiotic properties. Two indicators (upwelling zones and marine water quality parameters) were evaluated under Marine Water Quality; three indicators (non-native invasive marine species threat, number of marine native nuisance species, and priority habitats condition) have yet to be evaluated. Several indicators performed poorly against all criteria because we were unable to determine what they were an indicator of. These included the number of salmon net pens, number of oyster culture sites, and number of clam culture sites, and may better serve as 'pressure' indicators.

Table 17. Summary of Marine Habitats – Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Non-native invasive aquatic marine species has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Upwelling zones	Evaluated under Marine Water Quality			
Aggregation/deposition zones	3	5	1	Theoretically-sound. Could be a good leading indicator of habitat forming processes.
Marine water quality parameters	Evaluated under Marine Water Quality			
Harmful algal blooms (HABs) status & trends	3	7	2	Good indicator of habitat condition, but does not respond predictably to management actions or pressures b/c lack of understanding of the conditions for HAB formation. Monitoring needs to be spatially and temporally explicit b/c no way to forecast HABs more than 1-2 wks out; this increases costs.
Intertidal biotic community status & trends	0	4	0	Currently unable to find sufficient evidence supporting the use of this indicator.
Non-native invasive aquatic marine species	2	3	3	Possibly theoretically-sound. Lacking evidence explicitly linking presence/absence to changes in habitat condition. Some existing data in Puget Sound. Most useful if continuous monitoring for presence/absence throughout the Sound.
Non-native invasive marine species threat	Not yet evaluated			
Number of marine native nuisance species	Not yet evaluated			
Number of salmon net pens	0	0	0	Unable to determine what this is an indicator of – may better serve as a 'pressure' indicator.
Number of oyster culture sites	0	0	0	Unable to determine what this is an indicator of – habitat condition, water quality, or human health?
Number of clam culture sites	0	0	0	Unable to determine what this is an indicator of – habitat condition, water quality, or human health?
Priority habitats condition	Not yet evaluated			
Number of marine species at risk that are threatened/endangered /candidate	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of marine species listed under Federal ESA	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of marine species of concern on State list	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of marine species of greatest conservation need	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of marine species of conservation concern	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.

A subset of related indicators performed well against all criteria and included the number of marine species at risk that are threatened/endangered/candidate, number of marine species listed under Federal ESA, number of marine species of concern on State list, number of marine species of greatest conservation need, and number of marine species of conservation concern. These indicators were originally evaluated under Marine Species (population condition), but were moved to Marine Habitats because the absolute number of species on any of these lists is a better reflection of habitat or environmental condition. All were theoretically-sound, but because each indicator is a compilation of species, it is difficult to conclude whether they respond predictably to management actions. These indicators appear to convey redundant information. Information on these indicators was principally obtained through WDFW and the Washington Biodiversity Council.

Two indicators, aggregation/deposition zones and harmful algal blooms status and trends, performed well against primary and data considerations. The remaining indicators (intertidal biotic community status and trends and non-native invasive aquatic marine species) received poor evaluations. Monitoring efforts by WDFW, WDOH, WDNR, among others, provided important data sources for these evaluations.

Freshwater habitat indicator evaluation

Area and Pattern/Structure. O'Neill et al. (2008) identified three indicators for freshwater habitat area (Table 18) [34]. These indicators (freshwater physical habitat, floodplain connectivity, and instream habitat) have yet to be evaluated. As well as evaluating these indicators, it may be useful to develop additional candidate indicators for this section.

Table 18. Summary of Freshwater Habitats – Area and Pattern/Structure indicator evaluations.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Freshwater physical habitat	Not yet evaluated			
Floodplain connectivity	Not yet evaluated			
Instream habitat	Not yet evaluated			

Habitat Condition. Eighteen indicators of freshwater habitat condition were identified, half of which have not been evaluated (Table 19). Several indicators including max temperature, sediment loadings rate, stream and lake water quality parameters, and spawning habitat water quality, are evaluated under Water Quality though they do pertain to habitat condition.

Table 19. Summary of Freshwater Habitats – Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Number of freshwater species of conservation concern has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Max temperature	Evaluated under Freshwater Quality			
Sediment loadings rate	Evaluated under Freshwater Quality			
Number of fish barriers corrected	Not yet evaluated			
Percent of channel length armored	Not yet evaluated			
Number of artificial fish barriers	Not yet evaluated			
Stream water quality parameters	Evaluated under Freshwater Quality			
Lake water quality parameters	Evaluated under Freshwater Quality			
Spawning habitat water quality	Evaluated under Freshwater Quality			
Non-native invasive aquatic species threat	Not yet evaluated			
Number of freshwater native nuisance species	Not yet evaluated			
Non-native aquatic freshwater species	Not yet evaluated			
Priority habitats condition	Not yet evaluated			
Clean & cool water for salmon	Not yet evaluated			
Freshwater physical habitat condition	Not yet evaluated			
Number of freshwater species listed under the Federal ESA	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of freshwater species of concern on State list	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of freshwater species of greatest conservation need	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of freshwater species of conservation concern	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.

Evaluated indicators for freshwater habitat condition represent a group of related indicators that performed well against all criteria. These included the number of freshwater species listed under Federal ESA, number of freshwater species of concern on State list, number of freshwater species of greatest conservation need, and number of freshwater species of conservation concern. These indicators were originally evaluated under Freshwater Species (population condition), but were moved to Freshwater Habitats because the absolute number of species on any of these lists better reflects habitat or environmental condition. All were theoretically-sound, but because each indicator is a compilation of species, it is difficult to conclude whether they respond predictably to management actions. These indicators appear to convey redundant information. Information on these indicators was principally obtained through WDFW and the Washington Biodiversity Council.

Terrestrial habitat indicator evaluation

Area and Pattern/Structure. O'Neill et al. (2008) identified three indicators of terrestrial habitat area: terrestrial land cover status and trends, transportation impacts, and forests and forestry (Table 20) [34]. None of these indicators have been evaluated. This section may benefit from the addition of new candidate indicators, as well as evaluating the indicators currently identified.

Table 20. Summary of Terrestrial Habitats – Area and Pattern/Structure indicator evaluations.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Terrestrial land cover status & trends	Not yet evaluated			
Transportation impacts	Not yet evaluated			
Forests & forestry	Not yet evaluated			

Habitat Condition. There were nine indicators of terrestrial habitat condition identified (Table 21). Three indicators, old growth forest change, road densities, and priority habitats condition, have yet to be evaluated. Two indicators, non-native invasive terrestrial species threat and number of terrestrial native nuisance species, performed well against primary considerations but not data considerations. The Washington Invasive Species Council is leading efforts to compile numbers and occurrence data for these two indicators.

Table 21. Summary of Terrestrial Habitats – Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Number of terrestrial species of conservation concern has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Old growth forest change	Not yet evaluated			
Road densities – erosion	Not yet evaluated			
Non-native invasive terrestrial species threat	3	1	2	Theoretically-sound, but little data currently exists. WA Invasive Species Council leading efforts to compile numbers and occurrence data.
Number of terrestrial native nuisance species	3	1	2	Theoretically-sound, but little data currently exists. WA Invasive Species Council leading efforts to compile numbers and occurrence data.
Priority habitats condition	Not yet evaluated			
Number of terrestrial species listed under Federal ESA	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of terrestrial species of concern on State list	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of terrestrial species of greatest conservation need	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.
Number of terrestrial species of conservation concern	3	7	4	Theoretically-sound, although peer-reviewed evidence linking this with habitat condition is lacking. Difficult to say how this indicator responds predictably to management actions or pressures b/c it is a compilation of species. May be a good vital sign indicator. To avoid redundancy, choose one indicator of species conservation concern.

A subset of related indicators performed well against all criteria and included the number of terrestrial species listed under Federal ESA, number of terrestrial species of concern on State list, number of terrestrial species of greatest conservation need, and number of terrestrial species of conservation concern. These indicators were originally evaluated under Terrestrial Species (population condition), but were moved to Terrestrial Habitats because the absolute number of species on any of these lists better reflects habitat or environmental condition. All were theoretically-sound, but because each indicator is a compilation of species, it is difficult to conclude whether they respond predictably to management actions. These indicators appear to convey redundant information. Information on these indicators was principally obtained through WDFW and the Washington Biodiversity Council.

Interface habitat indicator evaluation

Area and Pattern/Structure. There were four indicators identified for interface habitat area (Table 22). Wetland acreage status and trends has not been evaluated. Two indicators, saltmarsh status and trends and riparian habitat, performed well against all criteria. In particular, riparian habitat fulfilled all of the primary considerations as well as most of the data considerations. Of note, saltmarsh status and trends did not fulfill the theoretically-sound criteria because it is most often used as part of an integrative assessment of ecosystem health, rather than a stand-alone indicator. Shoreline geomorphology received a poor evaluation because, while it is theoretically-sound and relevant to management, data trends are largely missing, especially as they relate to changes from natural versus anthropogenic impacts. Monitoring efforts by WDNR and Simenstad et al. [124] provided valuable data for these evaluations.

Table 22. Summary of Interface Habitats – Area and Pattern/Structure indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Saltmarsh status and trends has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Wetland acreage status & trends	Not yet evaluated			
Saltmarsh status & trends	3	7	4	Overall good indicator -- total area often used as integrative assessment of ecosystem health. May best be used as part of an integrative assessment of habitat change in the region.
Riparian habitat	5	6	3	Very good indicator of riparian ecosystem health including habitats and species. Evidence that restoration increases riparian habitat area. Good data for Puget Sound. May best be used as part of an integrative assessment of habitat change in the region.
Shoreline geomorphology	2	0	0	Poor indicator. While this indicator is theoretically-sound and relevant to management, it fails all other criteria. Indicator requires classification of shorelines, which groups throughout PS do differently. Also, difficult to determine (1) when one geomorphic type ends and another begins, and (2) natural vs. anthropogenic change.

Habitat Condition. Percent of shoreline armored, nearshore physical and biotic habitats, and wildlife status and trends in restored habitats were selected as indicators for interface habitat condition (Table 23). All were theoretically-sound and relevant to management. Percent of shoreline armored may be a good indicator, although explicit linkages between armoring and effects on biota is largely absent. Nearshore habitats met most of the data and other considerations, and may be useful as a leading indicator of how habitat-forming processes have been altered in the nearshore environment. Wildlife status in restored habitats appears to be costly and time intensive to measure. Principal data sources for these evaluations included monitoring efforts by WDNR, as well as Simenstad et al. [124].

Table 23. Summary of Interface Habitats – Condition indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Nearshore physical and biotic habitats has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Percent of shoreline armored	3	5	2	May be a good indicator, although there is not a lot of science concerning how this affects biota (i.e., difficult to determine whether it responds predictably to ecosystem attributes). Also, difficult to determine thresholds – how much armoring in an area is bad? Easily measured, and cumulative effects important especially in the context of other shoreline stressors.
Nearshore physical & biotic habitats	2	5	4	Theoretically-sound, although few studies relating shoreform change to nearshore ecological function. Primarily useful as a leading indicator of how habitat forming processes have been altered in nearshore (i.e., measures level of impairment to habitat forming processes).
Wildlife status & trends in restored habitats	2	2	0	Good measure of restored habitat's ecological function, but useful measures (growth, consumption, survival) rather than number and diversity are more costly and time intensive to measure. Data rarely available.

Water Quality Evaluation

Recently the PSP listed several contaminants of concern for Puget Sound organized into four general categories including toxics, nutrients, pathogens, and other (i.e. deviations in physical/chemical state of a water body; [125]). Specific issues related to these categories, including discussions on several chemicals of concern, have been detailed therein and elsewhere [76]. Nutrients and "other," will be discussed as physical/chemical parameters; toxics as trace inorganic and organic chemicals; pathogens, under the goal Human Health. ''' 5.4.1 Indicators of Hydrodynamics'''

Water circulation patterns in Puget Sound influence water quality. Freshwater inputs from rives and streams can create density stratification, which, in turn, can exacerbate conditions underlying eutrophication and hypoxia [126]. Washington State Department of Ecology reports on stratification based on frequency and intensity. Stratification intensity is based on change of seawater density (reported a sigma-t; density in kg m-3 – 1000) over the pycnocline. Frequency is determined by the percent of time that the change in density across the pycnocline is greater than two. Stratification patterns vary temporally and locally within Puget Sound; stratification is generally strongest near areas of freshwater inflow while vertical mixing occurs at sills [90]. Status and trends of stratification are discussed in the sections on hypoxia and marine eutrophication in Chapter 2 of the Puget Sound Science Update.

Marine circulation may be the largest factor in the delivery of nutrients to Puget Sound [86]. Periodic deep water intrusions over the entrance sill at Admiralty Inlet deliver marine waters into Puget Sound [88]. Deep water circulation and residence times vary throughout Puget Sound, and also interannually; interannual variations appear to be associated with variations in freshwater flows, and salinity at the Strait of Juan de Fuca [127, 128]. Large sale climate variations can affect upwelling off the Strait of San Juan de Fuca (and, thus, salinity), surface winds, temperatures, and precipitation, possibly influence Puget Sound's oceanography [89, 129]. Wind may be important driver on the circulation of Puget Sound. Wind has been implicated in causing outcrops of low-DO water in southern Hood Canal [88].

Although marine circulation patterns are likely important, particularly in terms of nutrient supply to Puget Sound, the magnitude, timing, and influencing factors are not well understood.

Indicators of Physical/Chemical Parameters

Physical and chemical parameters can define the state and status of water with regard to the health of humans and the environment. These include temperature (T), dissolved oxygen (DO), nutrients such as nitrogen (N) and phosphorus (P), chlorophyll, and the Secchi depth. These fundamental measures are often combined into various indices or states, depending on management concerns.

Low DO is of particular concern in marine waters, particularly in the Hood Canal and areas of South Puget Sound [76]. A discussion of the status and trends is included in Chapter 2 of this Puget Sound Science Update. A discussion of the potential biological effects of low DO are included in a literature review performed by the Washington State Department of Ecology as part of an evaluation of DO standards for marine and freshwaters [92, 130, 131]. A brief discussion of the DO standards is presented in Section 6.8.3.

Temperature is a critical measure and of importance to instream biota in streams and rivers of the region. A discussion of the biological impacts of temperature is included in the literature review performed by the Washington State Department of Ecology ([93]; see Section 6.8.3). There is currently limited evidence that temperature changes are important in the marine environment of Puget Sound.

Eutrophication, nutrients, chlorophyll, and Secchi depth are measures related to the productivity of a water body [86, 95-101, 132-135]. Marine eutrophication is discussed in Chapter 2 of this Puget Sound Science Update. An evaluation of the water quality criteria for phosphorus and its relationship to Secchi and trophic state has been performed by the Washington State Department of Ecology [136].

The Washington State Department of Ecology and King County utilize a freshwater Water Quality Index (WQI) to summarize water quality information in a format that is easily understood [137]. The WQI is based on T, DO, pH, fecal coliform bacteria (FC), TN, TP, total suspended sediment (TSS), and turbidity. Ranking factors are based on relations to state water quality standards (T, DO, pH, and FC; [138]), the limiting nutrient (TN or TP) or a calculated harmonic mean (TSS and turbidity). Evaluations of the WQI approach suggest that it be a communication tool (e.g. a reporting indicator) but not used for evaluation (e.g., an assessment indicator) since it does not reveal specific water quality traits [137, 139-141]. It has also been suggested that subjective, professional judgment be minimized in the development of WQIs by using published cause/effect relationships [142].

Rivers and streams in Canada utilize a Canadian WQI (CCME WQI) that is similar to the WQI developed by Washington State Department of Ecology. However the CCME WQI reflects Canadian standards and is adjusted by the scope, frequency, and amplitude of failed test values [143].

Marine WQIs are currently not used in the Puget Sound region, though one is under development. Washington State Department of Ecology has reported on areas where water quality is a concern by summing the results of five water quality indicators (stratification, DO, nutrients, FC, and ammonium; [126]).

Indicators of Trace Inorganic and Organic Chemicals

The marine waters and sediments of Puget Sound have been affected by different classes of anthropogenic chemicals (e.g. toxics); some have been well studied while others less so. Several efforts have been made to identify the chemicals of concern in Puget Sound based on historic monitoring programs [144-146]. These toxic chemicals included metals and metalloids (arsenic, cadmium, copper, lead, mercury, and tributyl tin), organic compounds (polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), pesticides, dioxins and furans, phthalate esters, polybrominated diphenyl ethers (PBDEs), and hormone disrupting chemicals. In 2007, the Washington State Department of Ecology, as part of a Chemicals of Concern work group, modified this list resulting in the following 17 chemicals of concern for marine waters [145].

- Arsenic
- Cadmium
- Copper
- Lead
- Mercury
- Total PCBs
- Low molecular weight PAHs
- Carcinogenic PAHs
- Other high molecular weight PAHs
- DDT and Metabolites
- Triclopyr
- Dioxins and furans
- bis(2-Ethylhexyl)phthalate Phthalate esters
- Total PBDEs
- Nonylphenol
- Oil or petroleum product
- Zinc

Subsequent evaluations added other broad categories of toxics including pharmaceuticals and personal care products [76, 147]. These are of concern because of their observed or presumed ability to cause harm to human health or the environment.

There are several state and local monitoring efforts, which address many of these chemicals of concern. Chapter 2 of this Puget Sound Science Update reviews the status and trends of Persistent Bioaccumulative Toxics (PBTs), which includes PCBs, PDBE, pesticides (i.e. DDT) and mercury, PAHs, metals, and endocrine disrupting chemicals.

The prioritization of toxics in water and sediments for monitoring, evaluation, and potential remediation is complex and difficult, particularly considering the vast array of emerging contaminants in aquatic environments [148]. In order to determine whether a compound is of concern it is necessary to understand its source, distribution, fate and transport, exposure and biotic effect. And, although a significant amount is known about certain toxics, very little is known about the majority of them [149]. The USGS performed a national reconnaissance, sampling in 139 streams and analyzing for 95 toxics and found a common detection of multiple contaminants in each sample [150]. Further sampling programs have been performed for groundwater and untreated drinking water sources [151, 152]. Similar suites of chemicals were found in the groundwater and untreated drinking water sources compared to the river and streams, though at a lower detection frequency and generally lower concentrations. Similar results have been reported for European sampling surveys [153, 154].

King County performed a preliminary survey of sixteen known endocrine disrupting chemicals in marine waters, lakes, rivers, and small streams [155]. Overall levels were similar to those found in national surveys. Specific compounds such as 17α-ethinylestradiol (EE2) and 4-nonylphenol were detected frequently and at maximum levels greater than the effective concentrations reported in the literature.

Emerging contaminants often occur at very low concentrations and in mixtures; accurate risk assessments may depend on the use of relevant exposure scenarios to capture potential synergistic or antagonistic effects [156]. For example, individual estrogenic chemicals can act additively, causing a response even when the concentration of each individual compound is below the known effective concentration [157]. In addition to endocrine disruption, environmental estrogen exposure has been reported to induce genotoxic damage, affect immune function, and alter metabolism in fathead minnows, [158]. Further, responses to EE2 may be different with mixtures of endocrine disruptors compared to EE2 alone, suggesting complex interactions.

This suggests that emerging contaminants are present in Puget Sound and may be environmentally significant. As such, indicators of water quality related to these trace inorganic and organic chemicals should be evaluated and selected carefully. Sumpter and Johnson suggest two possible approaches to evaluate the potential risks and effects associated with emerging contaminants [159]. One would be to use contaminant-specific information to identify possible exposure-effect relationships combined with hydrology to identify potential hotspots and focus analytical investigations. The second approach would begin with investigations of biota directed in specific locations by hydrologic modeling to determine if there are any identifiable adverse impacts. Both investigatory approaches may be useful in evaluating relative threats from emerging contaminants as the relative threats are currently not known.

The analytical-chemical approach and biota-observation approach are both used for monitoring water quality and the selection/utilization of specific indicators. One issue specifically related to the selection and evaluation of water quality indicators is whether they are better suited as indicators of water-quality or of species condition (or, perhaps, are good indicators of both). The Heinz Foundation (2008) reports contaminants in fish in shellfish as a measure of chemical contamination of the environment where as EPA's Science Advisory Board (2002) reports contaminants in tissue as a sign of disease potentially affecting species condition [42, 44]. For the purpose of this report we recognize contaminants in tissue (i.e. tissue residue levels) and biomarkers of contaminant effects as measures indirect indicators of water quality and direct measures of species condition, however species will vary in the ability to reflect local, regional and coastal water quality condition.

There are several indicators of contaminants in biota, which could be either measures of Water Quality – Trace Inorganic or Organic Chemicals, or Species – Population Condition. For example, the level of contaminants and/or liver disease in English sole has been shown to be strongly correlated with the level and presence of polycyclic aromatic hydrocarbons (PAH) in sediments, while also being a measure of species health [160-165]. This suggests that liver disease in English sole can be a suitable measure of general Marine Water Quality (i.e., PAHs in sediments) or of Species Population Condition.

Vitellogenin (Vtg) production in male fish may be another useful marker of environmental exposure to xenoestrogens [166] although unlike liver disease, the causative agent cannot be clearly identified. In Puget Sound, elevated levels of Vtg have been reported for English sole [167].

Recently, several studies investigating the causative action of xenoestrogens have implicated the disruption of steroidogenic acute regulatory (StAR) protein activity, which may be key in moderating the rate limiting step in steroid homone syntheses; evaluating StAR protein activity, then, may be a valuable biomarker for xenoestrogen exposure [168-170].

As these examples illustrate, the value of measuring biological response in biota (i.e. Vtg induction in male fish or liver disease in English sole) as an indicator or water quality is dependent largely on the strength of the knowledge of the exposure-effect relationship as well as the chemical specificity of the of the reaction. A lack of knowledge or a weak causal link would imply that the biological response were a poor indicator of water quality.

The concentration of specific contaminants in aquatic organisms may be appropriate indicators of water quality or species condition. Measurements of PAH, PCBs, PBDEs (and metals) and metabolites in fish tissues, primarily salmonids and bottom fish, and associated health effects, have been well studied in the region [171-175]. In some cases (i.e. PAHs, PCBs, and tributyl tin), the evaluation of tissue and sediment data have been used to establish sediments quality thresholds [164, 176, 177]. In other cases the presence of contaminants in biota may be reflective of environmental conditions, though health effects and thresholds are not well defined [178, 179].

The use of toxics in biota as indicators of water quality in Puget Sound is discussed below.

The NOAA National Status and Trends Mussel Watch Program has monitored contaminant concentrations in the coastal United States, including at least thirteen sites in Puget Sound, by sampling mussels, oysters, and sediments [180, 181]. Mussels have been shown to take up and accumulate the bioavaible fraction of hydrophobic contaminants from the water column [182]. Tissue concentrations of PAHs, total PCBs, and total DDTs were higher in mussels from the urban-associated sites compared to those from less urban areas; adverse health effects were observed [183, 184]. In Puget Sound, results indicated no significant trends at most sites, though several had decreasing trends and a few (Se) had increasing trends with time [180]. These results are discussed in Chapter 2 of this report. Toxics contaminants in mussels may be an appropriate indicator of water quality.

Tissue sampling of resident Pacific herring populations may allow for general indications of water quality. However, because herring populations range widely and feed on planktonic organisms (e.g., krill), their contaminant levels reflect conditions in the pelagic food web on a large, regional scale. West et al. (2008) was able to discriminate differences in contaminant levels between herring populations sampled from inner and outer Puget Sound (i.e. north and south of Admiralty Inlet) but not among inner Puget Sound populations [185].

Due to the lifecycle and migration traits, measures of toxics in adult salmonids may not be suitable as indicators of local or regional water quality [186]. It has been shown that over 98% of adult body mass of six Pacific salmon species and steelhead is acquired while feeding in marine waters [187] but populations of Pacific salmon among and within species vary considerably in their marine range and distribution. Adult Chinook salmon may accumulate over 95% of their persistent organic contaminant burden during their time at sea, with their final tissue contaminant concentrations reflecting the range of exposure throughout their marine water feeding areas [186, 188]. In contrast, recent work has suggested PCB concentration in tissues of localized outmigrating juvenile populations may be correlated with local sediment concentrations [189].

Tissue analysis of harbor seals in Puget Sound and Strait of Georgia found relatively high levels of PCBs, polychlorinated dibenzo-p-dioxins (PCDDs), and polychlorinated dibenzofurans (PCDFs), and that location partially explained the relative concentrations and the mixture profiles [190]. Weight of evidence suggests that harbor species are exposed to levels of contaminants that have the potential to cause adverse health effects [188]. Although the range of harbor seals is relatively small they consume a wide-variety of fish, both local and ranging, suggesting that harbor seal contamination may be somewhat disconnected from that of their local habitats. As such, they may not be useful as indicators of localized sediments or water column contamination. However, a food basket analysis indicated that variances of contaminant concentrations in harbor seal population could serve as indicators of food web contamination, and environmental contamination on a regional scale [189].

Tissue samples from free-ranging killer whales found very high levels of PCBs and also of PCDDs and PCDFs [188]. The increasing presence of PDBEs in the killer whale food chain may also be of increasing import [191]. The range of the killer whales, and the range of their diets, suggests that tissue contaminant levels may not correlate well with local or regional contaminant conditions [185]. These reports suggest that there are measures of toxics in biota may be suitable measures of water quality at local (e.g., bivalves) and regional (e.g., herring, juvenile salmonids, or Harbor seals) though appropriate selection is necessary depending on the management concern. Toxics in biota can also be utilized as measures of species condition, though the health effect thresholds are not always clear for all species of concern.

Evaluation of Water Quality Indicators

Fifty-seven water quality indicators were selected for evaluation, and thirteen were evaluated. In general the indicators that were evaluated performed well against the Primary Considerations. However, there were often gaps in data, either spatially or temporally.

Marine Water Quality

A summary of the evaluation of indicators of Marine Water Quality is shown in Table 24. The indicators of marine water quality generally performed well against the criteria suggesting that there are many acceptable indicators, which can be selected depending on the issue of management concern. Generally, the indicators evaluated under Physical/Chemical parameters performed well under the Primary Considerations, and the Data Consideration. However, there were often limitations in the spatial and historical extent of the data.

Table 24. Summary of Marine Water Quality indicator evaluations. The numerical value under each consideration represents the number of evaluation criteria supported by peer-reviewed literature. For example, the indicator Toxics in Mussels has peer-reviewed literature supporting 4 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary
Marine Water Quality				
Hydrodynamics				
Seawater stratification				
Upwelling zones				
Flushing rates				
Marine Water Quality				
Physical/Chemical Parameters				
Benthic infaunal community structure (sediment quality)				
Marine water quality index				
Nutrients in marine waters	5	4	3	Very important in specific nutrient limited locations (e.g. Hood Canal, Budd Inlet) though less so in main body of sound as it is generally not nutrient limited. High nutrients can lead to eutrophication and associated effects = high management concern. Management actions can affect some sources of anthropogenic nutrients. Reference points and targets are site specific and depend on historical state of water body. Certain areas of concern such as Hood Canal and Budd Inlet have good and sufficient coverage, though other areas is limited.
Sensitivity to eutrophication	0			Eutrophication is not a good indicator in itself. Eutrophication is characterized by a suite of measures such as DO, HABs, nutrients which are other specific indicators. Phytoplankton biomass is measured elsewhere. "Sensitivity," is not readily measured. Eutrophication is not directly measured nor is sensitivity to eutrophication. Makes this unsuitable for an indicator.
DO marine	5	4	4	DO levels affect marine species. Selected areas of low DO in Puget Sound are of great management concern. Management actions may have some impact on anthropogenic nutrient inputs to PS. Generally clear reference points and targets though may vary depending on historic conditions. Some areas of localized coverage, though not good historical record.
Marine water quality parameters				
WWTP nutrient hot spots				
Ratio of point to non-point nutrient loads				
Marine Water Quality				
Trace Inorganic and Organic Chemicals				
Toxics in English sole	5	5	4	Contaminant levels in English sole (including PAH metabolites in bile) increase with concentrations in the environment. Some metals (e.g.,Hg) are more sensitive to increase in fish age. Some metals (e.g. Cu) are regulated by fish and therefore tissue residues of Cu are not very sensitive measures of water quality. For example, tissue resides of Cu in Puget Sound marine fish do not vary among species or among locations within a species. Defined thresholds exist for some chemicals. Measurement and evaluation requires specialized techniques and instrumentation. Historic coverage of over 50 sites but spatial coverage was reduced in 2001 to 8 sites, representing urban, near-urban and non-urban site. Need to accounts for variation in age and lipid content of fish.
Liver disease in English sole				Prevalence of liver disease (i.e.toxicopathic hepaocellar lesion) is elevated in PAH contaminated environments. Changes in prevalence of iver disease are used to document reductions PAH environmental contamination associated with management strategies to reduce source control and remediate sediments. Thresholds for PAH levels in sediment associated with increased prevalence have been defined. Data collection requires technical expertise. Historic coverage of over 50 sites but currently limited to 8 sites representing urban, near-urban and non-urban site. Need 60 fish per samples location and % prevalence must be statistically corrected to account for age in the fish.
Toxics in clams				DOH and King County completed studies in the mid-90s but discontinued sampling in part because of low number of detects for organic compounds and variability of metals data, possibly associated with inconsistent species being sampled.
Fecal pollution index for commercial shellfish beds				
Chemical contamination in Puget Sound sediments				
Abiotic/pollutant exposure condition				
Toxics in crabs & shrimp				
Toxics in adult Chinook and Coho salmon	4	6	4	Toxics in biota generally reflect contaminants in their environment. High variability of toxic conc, especially for Chinook salmon associated with fish's residency in Puget Sound; tissue residue will vary substantially with changes in residency which may mask changes local water quality. Elevated toxics in salmon are pertinent to PSP goals for water quality, human health and species and food webs. Reflects toxics in marine waters throughout salmon's marine distribution. Data coverage includes populations returning to Nooksack, Skagit, Duwamish, Nisqually, and Deschutes rivers. Sampling from 1991; Chinook salmon discontinued in 2006. There is a low signal-to-noise ratio as residency of fish is often unknown.
Toxics in harbor seals	3	6	3	Some variability in tissue concentrations associated with variation in diet among seals from different sampling sites; reflects regional water quality (i.e. Georgia Bas vs, Puget Sound). Effects thresholds are based on captivity studies. Limited number of sample locations published to date. Archived samples for PCB and PBDE temporal trends at one locations.
Toxics in Pacific herring	5	8	4	Reflects toxics in marine waters throughout herring's distribution. Elevated toxics in Pacific herring are pertinent to PSP goals for water quality, human health and species and food webs. Concentration differences between northern Puget Sound and central Puget Sound are detectable. Specific threshold for herring exist of PAHs but not other chemicals. Coverage for major Puget Sound basins from 1999; no temporal trends observed.
Toxics in mussels	4	5	4	Data for toxics in mussel in Puget Sound are collected as part of NOAA's national Mussel Watch program. Number of sites is limited especially in southern Puget Sound. Currently a non-random sampling design is used. Threshold specific to the health of mussels are not know.
Fecal bacteria in offshore Puget Sound				
Fish Tissue Contaminants Index				Whole body samples of fish analyzed for contaminants, therefore not suitable for human health. Some problems interpreting data as species, sizes and ages vary among locations. Possibly combine these data with other Puget Sound datasets (e.g. ENVEST and WDFW).
Toxics in Osprey eggs				Only 2 stations are sampled in Puget Sound.
Oil Spills				
PCBs in Cormorant eggs				Data exist for the St. Georgia but limited data is available for Puget Sound
Star protein/ DNA damage				moved to species condition
Vtg induction in male fish	3	3	4	Elevated levels Vtg indicate exposure to xenoestrogens, including some trace organics. Various biological effects have been have been correlated with magnitude of Vtg induction in male fish but threshold will vary by species. Broad spatial coverage for English sole in Puget Sound. Limited time series data (e.g. 2-3 yr)s at some site. Very sensitive to changes in xenoestrogen.

There are several indicators concerning measures of contaminants in ecological receptors, which could be either measures of Water Quality – Trace Inorganic or Organic Chemicals, or Species – Population Condition (see section 5.4.3). The initial indicator organization placed these indicator based on trophic level and management concern. Low-trophic-level species were considered to be more directly exposed to environmental contaminants and thus more representative than were higher-trophic-level species. Toxics in species with high management concern were placed under population condition. The detailed evaluation process allowed for reorganization, as appropriate.

Interface Water Quality

A summary of the evaluation of indicators of Marine Water Quality is shown in Table 25. To date, only one indicator has been evaluated against the criteria.

Table 25. Summary of Interface Water Quality indicator evaluations. The numerical value under each consideration represents the number of evaluation criteria supported by peer-reviewed literature. For example, the indicator Toxics in Juvenile Salmon has peer-reviewed literature supporting 5 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary
Interface Water Quality				
Hydrodynamics				
Aggregation/deposition zones				
Interface Water Quality				
Physical/Chemical Parameters				
Sediment Quality Triad Index				
Wetland Water Quality Index				
Nearshore water quality				
Wetland water quality				
Interface Water Quality				
Trace Inorganic and Organic Chemicals				
Pesticide poisonings in raptors				Limited date is available for Puget Sound; consistently measurable, responsive to change. Limited study was not maintained.
Toxics in heron eggs				
Toxics in Juvenile Salmon	5	5	4	A consistent monitoring program for toxics in juvenile salmon does not exist for Puget Sound, however, multiple studies complete date, meet most of the criteria used to screen indicators.

Freshwater Quality

A summary of the evaluation of indicators of Freshwater Quality in shown in Table 26. There are several indicators of Freshwater Quality that meet the evaluation criteria. These include measures of contamination, nutrients, and general water condition. Generally, the indicators evaluated under Physical/Chemical parameters performed well under the Primary Considerations, and the Data Consideration with the exception that they were often limited in the spatial and historical extent of the data. No indicators have yet been evaluated under Toxic Organic and Inorganic Chemicals.

Table 26. Summary of Freshwater Quality indicator evaluations. The numerical value under each consideration represents the number of evaluation criteria supported by peer-reviewed literature. For example, the indicator Nutrient Loadings from Rivers to Puget Sound has peer-reviewed literature supporting 2 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary
Freshwater Quality				
Hydrodynamics				
see Water Quantity				
Freshwater Quality				
Physical/Chemical Parameters				
Sediment loadings rate				
Water Quality Index				
Nutrient loadings in rivers to Puget Sound	2	6	3	Nutrient loading to marine photic zone may be significant though possibly less important to overall N when compared to marine sources. Nutrient concentrations in streams is affected by land-use changes, though relationship is complex. Management actions are limited against non-point sources. Effects of nutrient loading sometime complex. Depending on receiving water, change in nutrient loading can affect eutrophication in a predictable manner
Trophic State Index - total phosphorous in lakes				
Dissolved Oxygen	4	5	5	DO levels have clear effects on biota in rivers and streams. DO effected by nutrients. Management actions are limited against non-point nutrient sources.
Water Temperature	4	5	5	Elevated temperatures have clear effects on biota in rivers and streams. Temperature may be controlled by riparian vegetation and/or stream flows. Management options may be complex.
Stream water quality parameters				
Spawning habitat water quality				
Lake water quality parameters - P, N, TSS, chl a,				
Stream C and N flow				
Watershed nutrient hot spots				
Freshwater Quality				
Trace Inorganic and Organic Chemicals				
Toxics in freshwater fish (multiple sources)				
Prespawn Mortality in Coho Salmon				
Toxics in water				
Toxics in freshwater fish (air deposition source)				
Fecal bacteria (streams)				
Indicator	**Primary Considerations (5)**	**Data Considerations (8)**	**Other Considerations (5)**	**Summary**
Biological Water Quality Index				

Indicators for freshwater hydrodynamics were evaluated under Freshwater Quantity – Surface Water Hydrologic Regime.

Next Step: Time constraints prevented a full evaluation of all water quality indicators in marine, freshwater and interface environments. An important next step is to complete the evaluation of water quality indicators.

Water Quantity Evaluation

There are over seventy USGS gauging stations on unregulated rivers and streams in Puget Sound, which are continuously collecting streamflow data. There are over 170 specific metrics that can be used to evaluate different aspects of streamflow. In order to determine which of these is most suitable for Puget Sound, we performed a review of the literature to determine salient management and scientific issues. The management issues of concern and potential indicators are listed below:

Management Issue	**Possible Indicator**
Climate Change	Stream hydrographs, Summer 7-day Annual Low Flow, Center of Timing (CT) of Annual Flow, Spring Snowpack (April 1 Snow-Water Equivalents)
Land use changes/urbanization:	Summer 7-day Annual Low Flow, Peak Flow, Flashiness (High Pulse Count)
Ecology	See above, Violations of Instream Flow Rules

These indicators and others were evaluated as described above. A summary of results is shown Table 27, Table 28, and Table 29. There are many possible indicators of Water Quantity that meet the evaluation criteria.

Table 27. Summary of Freshwater Quantity - Surface Water Hydrologic Regime indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Frequency of flood events has peer-reviewed literature supporting 4 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Surface water hydrologic regime				
High pulse count-	1	7	1	A good measure of flashiness which is a predicted alteration with urbanization/imperviousness. There are demonstrated correlations with Benthic Index of Biological Integrity though not with species of management concern. Management options to reduce hydrologic effects of land use change are limited. Good data.
T_{Qmean} -	1	7	1	A good measure of flashiness which is a predicted alteration with urbanization/imperviousness. There are demonstrated correlations with Benthic Index of Biological Integrity though not with species of management concern. Management options to reduce hydrologic effects of land use change are limited. Good data.
Degree of hydrologic alteration	0			Theoretically unsound. Not a clearly defined single measure, which can be utilized as an indicator.
Annual maximum daily flow / Winter peak flow	3	6	4	Increase in peak flows correlated with land use change and predicted result of climate change. May be important in salmon ecology. Important in flooding. Management options for mitigative actions are limited (particularly with climate change). Good data with the exception that some gauge station perform poorly with high flows. Possibly redundant with Occurrence of Peak Flows and Flooding Frequency.
Number of minimum flow days for each water year	2	8	4	Low flows predicted to increase due to effects of climate change, land use changes, and increased consumptive withdrawals. Important to water resource managers. Good data, though single drought event may disproportionally affect trends. Redundant with 7-day average low flows.
Occurrence of highest flow events per year	2	7	3	Increase in peak flows correlated with land use change and predicted result of climate change. May be important in salmon ecology. Peak flows more descriptive of flooding and flow timing. Good at demonstrating long term trends. Possibly redundant with Annual Maximum Flow and Flooding Frequency.
Spawning flows	1	8	1	Flows during spawning period may affect water temperature, habitat availabiliy, and energetics. Conditions vary depending on salmon run and river. Clear flow-response relationships not established due to potentially conflicting factors. Spawning flows may need to be definied for individual reaches and/or individual salmon runs. Salmon health of high management concern. Good data.
Percent of flows that create & maintain habitat	0			Theoretically unsound. Establishing flow-habitat relationships are complex and difficult to define. May vary between streams and reaches. Typically done for single species. Different species/habitat may require different aspects of flow for establishment (e.g. riparian vegetation require peak flows). Change in indicator may not be descriptive of important changes.
Percent of flows that meet summer base flows to support species	0			Theoretically unsound. Difficult to define due to the myriad of important habitats and the unique flow/habitat relationships that may exist on each river.
Annual mean flow streams and rivers	3	8	4	Important to water resource managers. May be affected by increased consumptive use. Limited magement options mainly concerning conservation and reuse. Good data. Indicator more descriptive when combined with other indicators of hydrologic alteration.
April and May Snow Water Equivalents (SWE), Spring Snowpack	3	6	4	Observed past and predicted future decreasing trends due to climate change. Important to water resource managers. Long term changes would alter flow regimes, which is potentially ecologically important. Management resoponses limited. Good data. Can be complimentary or redundant (7-day low flow, flow timing) depending on suite of indicators.
Glacier mass balance	2	4	3	Observed and predicted future changes due to climate change. Important to water resource manager. Long term changes would alter flow regimes, which is potentially ecologically important. Management resoponses limited. Moderate data.
Annual Center of Timing (CT)	3	7	2	Observed and predicted future changes due to climate change. Important to water resource manager. Long term changes would alter flow regimes, which is potentially ecologically important. Management resoponses very limited. Good data. Good complimentary with other indicators of hydrologic alteration.
Violations of DOE instream flows	3	8	3	Good indicator of management effectiveness. Instream flow rules may not be proctective of ecology. Good range of possible management responses. Good flow data. Instream flow rule only established on limited number of streams in Puget Sound. Somewhat redundant with 7-day Average Low Flow and Number of Minimum Day Flows per Year
Storm water quantity	Not yet evaluated			
Frequency of flood events	4	7	4	Predicted increased flooding with urbanization due to higher runoff from impervious surfaces. Higher winter flooding due to climate change due to more winter rain instead of snow, and rain-on-snow events. Important to management. Limited management responses. Established floodstage targets. Good flow data. Possibly redundant with Annual Maximum Flows or Occurency of High Flow Events.

Table 28. Summary of Freshwater Quantity – Groundwater Levels and Flow indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Annual 7-day low flow has peer-reviewed literature supporting 3 out of 5 Primary Considerations criteria. Details can be found in the accompanying spreadsheets.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Groundwater levels and flow				
Groundwater elevation/flows	Not yet evaluated			
Annual 7-day low flow	3	8	5	Predicted decrease in summer flows with climate change and increased consumptive use. Several studies show GW/surface water interactions with potential implications of low flows. Important ecologically. Important to management. Limited management responses. Good data. Complimentary with other indicators of the hydrologic flow regime. Somewhat redundant with Violations of Instream Flow and Number of Minimum Day Flows per Year.

Table 29. Summary of Freshwater Quantity – Groundwater Levels and Flow indicator evaluations.

Indicator	Primary Considerations (5)	Data Considerations (8)	Other Considerations (5)	Summary Comments
Consumptive water use and supply				
Storage days remaining	Not yet evaluated			
Water use/demand	Not yet evaluated			
Summer/autumn reservoir inflows	Not yet evaluated			

Surface Water Hydrologic Regime – Overview

The Puget Sound basin includes at least thirteen major river systems and numerous tributaries, which can be classified as rainfall-dominated, snowmelt-dominated, or transitional [191-193]. Rainfall-dominated rivers exhibit peak flows during winter; snowmelt-dominated rivers have peak flows in late-spring and late-fall with low winter flows. Transitional rivers exhibit less pronounced high or low flows in the late-Fall and late-spring, and winter. Hydrologic flow patterns are important both ecologically and in terms of consumptive resources. Alteration of historic flow patterns may cause ecological harm and supply disruptions [23, 80]. Hydrologic flow regimes in Puget Sound rivers have been altered through the construction of dams for flood control or power generation, or by changes in land cover and climate. Flows in the Skagit, Nisqually, Green, Skokomish, and Cedar rivers are regulated by dams [76].

There are over seventy USGS gauging stations on unregulated rivers and streams in Puget Sound. As such, there are ample data available for flow analysis and it is possible to use this data to evaluate streamflow patterns in many different ways. In order to determine which is the best way to analyze the data it is important to consider what are the most significant ecological and management concerns of the region. The bulk of this section presents a literature review that is intended to determine the important management and ecological issues of Puget Sound.

Indicators of Hydrologic Alteration

The surface water hydrologic regime of a river or stream can be characterized through measures of magnitude, frequency, duration, timing, and rate of change [174]. At least 170 specific metrics have been used to describe specific aspects of the hydrologic regime resulting in the potential for considerable redundancy [108]. The most suitable metric, or suite of metrics, is dependant on the specific nature of the question being addressed or the issues that are of greatest management concern [32, 63, 64].

The Puget Sound Partnership (PSP) has identified the following issues of potential concern related to water quantity in Puget Sound:

- Consumptive use of surface and groundwater;
- Changes in hydrology related to land use;
- Climate change;
- Modification to stream and floodplain habitats [125]

A stated goal of the management of water quantity in Puget Sound is:

- In-stream flows directly support individual species and food webs, and the habitats on which they depend [1].

The intent of this section is to describe the process of determining an appropriate set of indicators of hydrologic alteration, which are relevant to management concerns. Indicators will also be screened according to the criteria discussed elsewhere in this Puget Sound Science Update.

The following sections describe a review of the recent literature with geographic focus on Puget Sound. There were two objectives of the literature review: 1) determine which of the indicators of hydraulic alteration would be most appropriate based on the predicted or observed alternations related to land use change and climate change, and 2) determine which aspects of the flow regime are known to be most relevant to the aquatic species in Puget Sound streams and rivers.

Discussions of consumptive water use and habitat alterations are elsewhere.

Indicators of Hydrologic Alteration – Climate Change

Indicators of Hydrologic Alteration – Climate Change – Summary

- Analysis of historic streamflow data in the Western United States suggest that spring snowpack is decreasing and streamflow timing is getting earlier in the water year. These trends are apparent despite significant annual and systematic variation associated with the El Niño/Southern Oscillation and the Pacific Decadal Oscillation.

- Temperatures in the Puget Sound region are projected to increase an average of approximately 0.3°C per decade over the 21st century due to climate change.
- Increasing temperatures may lead to decreased spring snowpack, earlier spring runoff, and lower summer flows.
- Climate change associated hydrologic alterations may lead from snowmelt or transition (snow-rain) flow patterns to rainfall dominated flow patterns.
- Decline in snowpack may be problematic for regional water supplies as most systems have been developed base on historic flow patterns [194]

Indicators of Hydrologic Alteration – Climate Change – Literature Review

Puget Sound river hydrology may be affected by climate change. Precipitation in the region occurs predominately in the winter months. The accumulation of snow in the mountains is a primary storage mechanism particularly for the snowmelt-dominated and transitional river systems. It has been estimated that upwards of 70% of total stream discharge in the Western United States is from melting snowpack [192]. An estimated 27% of summer streamflow of the Nooksack river originates from high-elevation snowshed and glacier-derived meltwater [193]. Climate change assessments have predicted increased winter and spring temperatures resulting in decreased snowpack storage in the mountains, increased winter runoff as more precipitation falls as rain, and lower summer flows [83, 192, 197-200]. Climate change may force rivers with snowmelt-dominated and transitional hydrological flow patterns toward rainfall-dominated hydrology [194].

Prediction of the regional impacts of climate change on river and stream hydrology can be confounded by typical variation in rainfall patterns, high geographic variability, and land use changes. There are at least two large-scale systems that affect the annual climate variations in the Pacific Northwest [201]. The El Niño/Southern Oscillation, with a period of 2 to 7 years, and the Pacific Decadal Oscillation (PDO), with an estimated half-period of 20 to 30 years. Warm and cool phases of the El Niño/Southern Oscillation and/or Pacific Decadal Oscillation may result in variations on the order of 1°C for temperature, and 20% for precipitation [201]. Hamlet et al. (2005) utilized a Variable Infiltration Capacity model to discern long-term trends in spring snowpack from temperature and precipitation variability [195]. They found that downward trends in snowpack associated with temperature were related to widespread warming. Trends of snowpack associated with precipitation were largely controlled by decadal oscillations; climate change effects on precipitation have not been detected [196].

Mote et al. (2008) concluded that the primary factor in decreasing snowpack in the Washington Cascades was rising temperatures, consistent with the global warming [196]. The long-term snowpack trends were unrelated to the variability brought about by Pacific oscillations (e.g., PDO).

Casola et al. (2009) investigated the potential impacts of climate change on snowpack by combining future temperature predictions with the estimated temperature sensitivity of spring snowpack [203]. They utilized four distinct methods to estimate sensitivity and all four converged on a result of approximately 20% loss in spring snowpack per 1°C temperature rise. Analysis of historic and projected temperature data indicated that snowpack reductions over the past 30 years ranged from 8%-16% while future temperature change would result in an 11%-21% reduction in spring snowpack by 2050. However, future trends may not be statistically detectable due to a high level of interannual variability.

Barnett et al. (2008) utilized a multivariate analysis to evaluate the simultaneous changes in average winter temperature, snow pack, and runoff timing in the Western United States (including the Washington Cascades) for the period from 1950 – 1999 [83]. They found significant increasing trends in winter temperature, and decreasing trends in snow pack and runoff timing (indicating earlier snowmelt). In order to distinguish natural variation from anthropogenic forcing they evaluated the observations against two separate climate models and found that the hydrologic changes were both detectable and attributable to anthropogenic forcing.

Stewart et al. (2004) investigated historic (1948-2000) and future streamflow timing in snowmelt dominated rivers and streams in the Western United States [197]. They found significant trends towards earlier runoff in many rivers and streams in the Pacific Northwest. Utilizing a 'Business-as-Usual' emissions scenario with a Parallel Climate Model, they predicted a continuation of this trend, largely due to increased winter and spring temperatures but not changes in precipitation. In a companion study they further analyzed the trends in streamflow timing with variations of the PDO [198]. While streamflow timing was partially controlled by the PDO there remained a significant part of the variation in timing that was explained by a longer-term warming trend in spring temperatures.

Luce and Holden (2009) utilized quartile regression to investigate the trends in streamflow in wet (75th percentile), dry (25th percentile), and average (50th percentile) water years in rivers in the Pacific Northwest [199]. They reported that the highest proportion of significant decreasing trends occurred during the dry years, while there were few significant trends in the high flow years, concluding that the dry years were getting dryer in the Pacific Northwest. This aspect of the trends accounted for much of the increased variability in annual streamflow.

Recently, the Climate Impact Group, part of the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) at the University of Washington performed The Washington Climate Change Impact Assessment. The assessment included analyses on hydrology and water resource management in which they utilized results from 20 global climate models and two emissions scenarios from the IPCC Special Report on Emissions Scenarios (A1B and B1) to evaluate projected changes in spring snowpack and runoff [200]. For the rivers in the Puget Sound basin they found a dramatic decrease in spring snowpack with there being almost no April 1 snowpack by 2080. During that period, river hydrographs progressively changed from transition or snow-rain dominated to rain dominated patterns. There was little predicted change in annual precipitation.

Indicators of Hydrologic Alteration – Climate Change - Relevant Indicators

Based on the review of the literature, the following indicators of hydrologic alteration may be suitable to monitor and evaluate potential changes in the hydrologic regime brought about by climate change:

- Stream hydrographs
- Summer 7-day Annual Low Flow
- Center of Timing (CT) of Annual Flow
- Spring Snowpack (April 1 Snow-Water Equivalents)

Indicators of Hydrologic Alteration – Land Use/Urbanization

Indicators of Hydrologic Alteration – Land Use/Urbanization – Summary

- Puget Sound region has experienced extensive development and urbanization. The population of the 12 counties surrounding Puget Sound was approximately 4.2 million in 2005; it is expected to increase to 5.5 million by 2025 [201].
- Land use changes associated with increases in population affect river and stream hydrology. Typical changes include reduced infiltration and increased runoff, increased flashiness, and decrease in summer flows.

Indicators of Hydrologic Alteration – Land Use/Urbanization – Literature review

Alterations in land use can affect stream and river hydrology in various ways (see [80] and references therein). Urbanization is associated with the increase of impervious surface area, which can result in increases the severity and frequency of peak stream flows by reducing infiltration and increasing runoff; overall annual stream flow volumes are generally not affected [209-215]. Urbanization my lead to lower base flows from reduced infiltration, though this effect can be somewhat offset by a reduction in evapotranspiration from the clearing of trees [212]. The construction of storm drain systems has been implicated as a primary factor in the reduction a base flows [202]. Logging of forested lands increases annual flow by reducing evapotranspiration in the watershed though other hydrologic changes such increasing flooding are disputed [217-219]. River basin land use alterations may lead to alterations in channel morphology which can exacerbate flooding potential without changes in stream flow [203].

Burges et al. (1998) compared hydrology from a forested and a developed basin in Puget Sound lowlands [204]. They found that surface runoff accounted for 12%-30% and 44%-48% of rainfall on forested and developed catchments, respectively, suggesting that the rate of infiltration was much higher in the forested basin. In a similar study, Leith and Whitfield (2000) found an increased streamflow in basins with the most increase in urbanization compared to basins with less development [205]. Moscript and Montgomery (1997) found an increased flood frequency in streams with urbanized watersheds compared to nearby control watersheds, which had not undergone development [206].

Konrad and Booth (2002) investigated possible hydrologic effects related to urbanization by evaluating stream flow statistics from ten streams in the Puget Sound basin [207]. They found that the fraction of the year that flow was above average annual flow (TQ,mean) and the maximum annual flow (Qmax) had significant trends in the urbanized basins compared to the rural basins and could be useful in monitoring the effects of urbanization on stream hydrology. They suggested that TQ,mean might be of more practical use. Fleming (2007) analyzed the effects of urbanization by examining stream memory (i.e. the effect of prior stream flow on current discharge) in urbanizing and rural watersheds in the Puget Sound lowlands [208]. He reported that memory decreased in the developed basin over time but not the undeveloped basins, suggesting that flow memory would be a useful measure of development in a watershed, though may be dependent on basin size, with larger basins exhibiting a greater fidelity in memory.

Cuo et al. (2009) utilized a Distributed Hydrology-Soil-Vegetation Model in order to determine the relative effects of land cover and temperature change on the flow patterns in Puget Sound streams [211]. They found that the relative importance of temperature and land cover differed between the upland and lowland basins. In the lowland basins land cover changes were more important and generally resulted in higher peak flows and lower summer flows primarily from increased runoff. Both land use change and climate effects were more important in the upland basins. Climate effects were more important in the transitional zones and resulted in higher winter flows, earlier spring peak flows, and lower summer flows.

Indicators of Hydrologic Alteration – Land Use/Urbanizations - Relevant Indicators

Based on the review of the literature, the following indicators of hydrologic alteration may be suitable to monitor and evaluate potential changes in the hydrologic regime brought about by land use/urbanization:

- Summer 7-day Annual Low Flow
- Peak Flow
- Flashiness (High Pulse Count)

Hydrologic Regime – Ecology 5.5.2.2.5 Hydrologic Regime – Ecology – Summary

- Aquatic species in Puget Sound rivers and streams are generally adapted to historic flow patterns.
- Salmonid species appear to be sensitive to land use changes in watersheds with streams in urban areas being associated with less robust populations of coho compared to forested areas.
- Benthic invertebrate communities appear to be negatively affected by increased flashiness of stream hydrology associated with urbanization.

Hydrologic Regime – Ecology – Literature Review

The alterations of river and stream hydrology can affect aquatic ecosystems by changing physical habitats, disrupting the natural connectivity of habitats, or by facilitating the successful invasion of exotic species [224]. Native species may have evolved according to the pressures and timing of natural flow regimes; altering flow patterns may negatively affect those species [225]. However, it is not always possible to separate the biological impacts of altered river or stream hydrology from the biological impacts associated with the land-use changes that often accompany or force the alteration in hydrology.

Several studies have attempted to evaluate the ecological impacts of altered land use in stream and river watersheds in Puget Sound. Spawner survey data collected by Moscript and Montgomery (1997) suggested a decline in salmon populations in basins that underwent urbanization, but not in a nearby control basin [206]. Scott et al. (1986) compared fish populations in a urbanized stream with a nearby unaffected control stream and found that while overall fish biomass was similar between the two sample sites there were differences in species composition [209]. The urbanized stream population was dominated by cutthroat trout while the control stream population consisted of a wide array of salmonids, including coho, and non-salmonids.

Pess et al. (2002) performed a broad-scale analysis over 16 years to investigate salmon abundance with land use and habitat in the Snohomish river basin [210]. The proportion of adult coho supported by a particular stream reach was consistent over the course of the study and the median adult coho density was consistently higher in the forested areas compared to the more-developed areas.

Bilby and Mollot (2008) compared the distribution of spawning coho salmon in four Puget Sound rivers with changes in land use between 1984 and 1991 [211]. They found that, while the overall numbers of spawning coho changed at all sites, there was an approximately 75% reduction in the proportion of salmon spawning in areas of increased urban land use as well as a smaller decline in areas with increased agricultural land use activities. They suggested that the protection of spawning habitat may be important.

While these studies demonstrate relationships between urbanization and ecology, and urbanization has been shown to affect stream hydrology, there are several other factors, including an increase in contamination input from surface runoff and habitat modification, which likely influence the results [212]. There are several are several other studies which have attempted to elucidate the specific effects of hydrologic changes on in-stream ecology, including fish and benthic invertebrates; these are discussed below.

High flows can affect salmon returns by disrupting redds, increasing deposition of fine sediments and reducing dissolved oxygen transfer, reducing growth rates, or increasing downstream displacement and mortality [225]. In a Puget Sound stream, egg burial depths were observed to be slightly deeper than typical scour depths caused by flooding during the incubation period suggesting an adaptation to environmental flow conditions [213]. Increases in peak flow due to land development or other causes may then significantly contribute to embryo mortality. Schuett-Hames et al. (2000) also investigated scour depth in two locations in a Puget Sound lowland stream [214]. They observed sediment scour during two storm events with estimated return intervals of 1 and 1.4 years and found that scour depths reached median egg pocket depths at 20% of the monitored sites during the larger storm. This suggests that scour related to high flows may be important in salmon mortality in Puget Sound.

Beamish et al. (1994) identified an inverse relation between anomalously high flows and indicies of production for coho and Chinook salmon in the Frasier River but not for chum, pink, or sockeye salmon suggesting that, at least in some cases, extreme flows may affect survival [215]. They did not identify a causative mechanism.

Greene et al. (2005) utilized standard multiple regression analysis to evaluate correlations between various environmental factors in the freshwater, bay/delta, and ocean habitats and the return rates of Chinook salmon in the Skagit River [232]. Their results indicated that flood magnitude, as measured though the Flood Recurrence Interval of the peak flow during incubation period, was a strong predictor of the return rate for Chinook salmon; there was a negative correlation between flood magnitude and salmon returns. A bay habitat factor, which was calculated based on measures of sea level, sea level pressure, and upwelling, was also significantly correlated with Chinook return rates.

In order to evaluate the overall effects of anthropogenic changes on salmon abundance, Scheuerell et al. (2006) utilized a multistage model to incorporate population growth, habitat attributes, hatchery operations, and harvest management based on predictive relationships from the published literature [233]. Relationships between peak daily flow during incubation period to egg-to-fry survival rate for Chinook or sockeye have been reported for Puget Sound rivers [234-237]. Although the reported data generally indicate a decrease in egg-to-fry survival with increasing peak flow during incubation period, the apparent best-fit regression (i.e. negative exponential, logarithmic, or linear) varies, demonstrating the uncertainty in the relationship. Battin et al. (2007) utilized the same relationship but also considered the potential limitations on spawning capacity that could be brought about by minimum flows during the spawning period [216]. They found that the model results were relatively insensitive to spawning capacity (and minimum flows).

Summer flows have been shown to be correlated with coho run strength in Puget Sound [217].

Bauer and Ralph (2001) evaluated the potential utility of incorporating aquatic habitat indicators, including those related to flow regime, into legal standards for water quality [218]. However, they concluded that the effects of low flow on habitat availability was sufficiently well understood to only allow the development of narrative, but not numeric criteria; the relationships between peak flows and habitat were less certain.

Similarly, Poff et al.(2010) recently reviewed 165 papers to investigate the possibility of developing quantitative relationships between various types of hydrologic alteration and ecological response [81]. While there was a general reported decline in ecological metrics in response to changes in flow metrics, including a general decline in fish abundance and diversity with alterations in flow magnitude, they were unable to support any quantitative relationships.

Matzen and Berge (2008) evaluated the relationship between urbanization and fish populations in Puget Sound lowland streams through the development of a fish index of biotic integrity (F-IBI; [219]). Due to the low species diversity characteristic of Puget Sound lowland streams, they utilized several metrics, which were specific to the region; the final F-IBI included a combination six metrics, which showed the strongest correlation to TIA. The authors cautioned against the direct comparison of individual IBI scores, or the value of short-term trends due to the likelihood of spatial or temporal variation that can occur within streams.

There are several studies that evaluate the effects of urbanization on stream condition based on a benthic index of biological integrity (B-IBI). Morley and Karr (2002) investigated the relationships between stream biological condition, as measured by the B-IBI, and the extent and distribution of urbanization, and stream flow in Puget Sound lowland streams [220]. They reported that B-IBI was significantly correlated with urbanization, as measured by percent urban area and percent impervious area in a sub-basin. Further, they found that B-IBI was correlated with measures of flashiness though not peak flow, and relative roughness though not measures of pebble or fine diameter (e.g. D16 or D50). Based on these relationships they argued that benthic invertebrates were a key measure of stream condition, though not necessarily predictive of the condition of fish populations.

Booth et al. (2004) reported similar correlations between B-IBI and percent urbanization, percent imperviousness, and several measures of flashiness [213]. They did not conclude that urbanization would be a good predictor of stream health but rather suggested that levels of urbanization may constrain the potential benthic diversity of a particular stream and that urbanization may affect each stream differently.

Bond and Downes (2003) performed a set of controlled studies and found that flow increases, but not changes in fine sediment transport, were sufficient to disturb benthic communities in streams, though the effects may be dependent on the availability of flow refugia [221]. This is consistent with studies, which suggest that benthic diversity is sensitive to hydrologic alterations brought about by urbanization.

King County investigated the relationships between flow alterations and in-stream ecology in Puget Sound lowland streams through the Normative Flow Project [222]. They used data from a set of locations representing a range of land cover conditions to evaluate the effects of land use on hydrology and biological condition, as measured through the B-IBI and other macroinvertebrate metrics. The hydrologic metrics with the strongest correlation with B-IBI included low-flow threshold pulse events and interval between pulses, high-flow threshold pulse events and total period of the year with high pulses, TQmean, percent of time above the mean two-year flow, and timing of the onset of fall flows. Although none of the hydrologic indicators were good predictor of B-IBI they were able to discriminate the difference between high and low B-IBI values.

Alberti et al. (2007) evaluated the patterns and connectivity of urbanization by performing an empirical analysis of land use intensity, land cover composition, landscape configuration, and connectivity of the impervious area, on B-IBI in Puget Sound lowland streams [245]. Their analysis suggested that total impervious area (TIA) explained much of the variance in B-IBI across basins, but other factors such as mean patch size of urban land cover and number of roads crossing a stream could explain part of the variance not explained by TIA alone. They also reported an inverse relationship between the aggregation of forested land and B-IBI suggesting that intact forests are important to benthic diversity.

DeGasperi et al. (2009) performed a retrospective analysis to relate measures of hydrologic alteration that were sensitive with measures of urbanization and benthic diversity, but not sensitive to basin area [106]. They found that high pulse count (the discrete number of high pulses per water year when flow is exceeds twice the average annual flow rate) and high pulse range (the number of days from the first high pulse to the last high pulse in the water year) best fit their evaluation criteria. Their analysis suggested as a basin is urbanized the number of high pulses increase in the winter and are more likely to occur in the summer increasing both the discrete number of pulses and the range. These pulses affect appear to affect B-IBI values.

Although the B-IBI score may be correlated with specific types of hydraulic alteration which specifically affect benthic communities, there is no clear relationship between B-IBI and the condition of vertebrate species [220]. Further, the natural variability of biological indices has not been well characterized; large variability may lead to inaccurate determinations of river health [246]. There can be both large and small scale spatial variability as well seasonal and inter-annual variability, all of which needs to be well understood in order to correctly attribute changes in biological condition with physical alteration brought about by anthropogenic activities. Mazor et al. (2009) found fluctuating conditions at sights without obvious changing conditions suggesting that short-term bioassessments may lead to inaccurate conclusions [246].

Summary of Water Quantity Indicators

A summary of the indicator evaluation in presented in Table 27, Table 28, and Table 29. In summary there is a wide range of possible indicators of the Surface Water Hydrologic Regime, which perform very well under both the Primary and Data Considerations. There is ample data for the region that can be parsed and evaluated in many different ways. It is, therefore, essential to understand the management concern or objective prior to indicator selection to ensure that the indicator is appropriate to the question at hand.

Only a single indicator was evaluated for groundwater levels and flows. It performed well against the Primary and Data considerations. However, owing to subsurface heterogeneity, the spatial variation is often not well understood, nor is it possible to confidently infer condition at on location from based on data collected proximally.

No indicators were completely evaluated for consumptive use and supply. However, a preliminary review suggests that there are good performing indicators, though it may be a time-consuming task to collect and compile the data on a regional scale.

Key Point: There is ample data to support the use and continued development of water quantity indicators. However, different indicators will better form different management concerns or objectives. Thus, prior to indicator selection it is critical to precisely define the management goal and operational objectives.

Ranking Puget Sound Indicators

Terminology and concepts	
Ecosystem assessment indicator	Technically robust and rigorous metric used by scientists and managers to understand of ecosystem structure and function
Improving indicator	Indicator that is increasing faster in the short-term but slower in the long-term than an index that captures aggregate changes in multiple indicators
Lagging indicator	Indicator that is increasing slower in the short- and long-term than an index that captures aggregate changes in multiple indicators
Leading indicator	Indicator that is increasing faster in the short- and long-term than an index that captures aggregate changes in multiple indicators
Other considerations	Indicator evaluation criteria that make an indicator useful, but without which an indicator remains scientifically informative
Ranking scheme	Approach used to weight indicator evaluation criteria
Slipping indicator	Indicator that is increasing faster in the long-term but slower in the short-term than an index that captures aggregate changes in multiple indicators
Vital sign indicator	Scientifically meaningful, but simple, metric that can generally inform the public and policy makers about the state of the ecosystem

The matrix of ecosystem indicators and indicator evaluation criteria provides the basis for ranking indicators. However, ranking indicators requires careful consideration of the relative importance of evaluation criteria. The importance of the criteria will certainly vary depending on the context within which the indicators are used and the people using them. Thus, ranking requires that managers and scientists work together to weight criteria. Failure to weight criteria is, of course, a decision to weight all criteria equally.

As an example of how our matrix could be used to rank indicators, we compare two food web indicators, ratfish/flatfish and jellyfish, using different weighting schemes. We provide these examples simply as an illustration, not to advocate one weighting scheme versus another.

One could begin by scoring each indicator as 1.0 when there is peer-reviewed evidence that that it met a criterion. When there is non-peer reviewed or ambiguous evidence that an indicator meets a criterion we give it a score of 0.5. When it does not meet a criterion, it receives a score of 0.

Equal weights: In this first scheme, we weight all criteria equally. In this case, ratfish/flatfish get a score of 10.5, while jellyfish score a 10 (out of a possible 19).

New monitoring programs: Imagine, however, a case in which the availability of historical data is less important (e.g., when considering a new monitoring program). In this instance, one might wish to ignore data considerations such as "historical data available", "broad spatial coverage", "continuous time series", and "variation understood". In this scheme, the ranking of the indicators reverses with jellyfish scoring 9.5, while ratfish/flatfish score 8.5 (out of 15).

Discounting importance of peer-review: Our initial weighting discounts indicators that were not supported by peer-reviewed evidence. It is conceivable that in some settings practitioners might wish to equally weight non-peer and peer reviewed evidence. In this case, because much of the evidence supporting the data criteria for ratfish/flatfish is not in peer-reviewed literature, the score for this indicator would increase to 14.5 (out of 19).

Whatever ranking scheme is used, our matrix can serve as a useful starting place for sorting through large numbers of indicators. By carefully ranking indicators in a manner consistent with specific management and policy needs, and choosing to focus on high-ranked indicators for each attribute, a winnowing of indicators naturally takes place.

Specificity and sensitivity of indicators

Long lists of indicators can present challenges for drawing inference about overall ecosystem status. A useful way to interpret lists of indicators in aggregate focuses on one of the primary considerations in the set of evaluation criteria introduced above, "the indicator responds predictably and is sufficiently sensitive to a specific ecosystem attribute." Two of the terms in this criterion, "specific" and "sensitive," can be used to organize indicators according to the type of information they provide about attributes. Rapport et al. (1985) proposed that an indicator's specificity can be distinguished based on whether it reliably tracks few or many attributes [5]. An indicator that provides information about many attributes (even attributes of multiple PSP goals) is non-specific but perhaps broadly informative of ecosystem status. An indicator that serves well as a proxy for fewer attributes can be thought of as diagnostic of changes in specific ecosystem characteristics. For example, in Figure 8 harbor seals are a non-specific indicator for Species and Food Webs attributes whereas jellyfish are a diagnostic one.

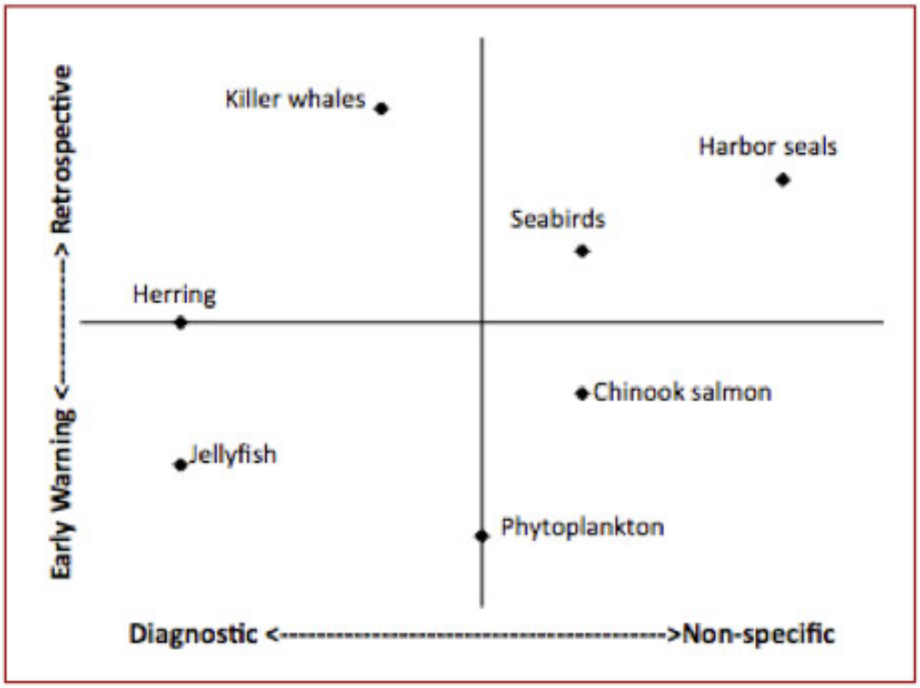
Another informative axis on which to interpret an indicator is in terms of its sensitivity. An indicator that provides information about impending changes in attributes before they occur is an early warning or "leading" indicator. For instance, due to fast turnover rates, phytoplankton are likely to be an early warning indicator for Species and Food Web attributes in Puget Sound (Figure 8). In contrast, an indicator that reflects changes in attributes only after they have occurred is a retrospective or "lagging" indicator. Retrospective indicators, such as killer whales (Figure 8), are likely to be characterized by slow turnover rates, but can nonetheless be useful for interpreting cumulative impacts and ecosystem-wide shifts in attribute values.

Vital Sign vs. Assessment Indicators

Ranking schemes provide a mechanism for narrowing the long list of indicators presented above to a more manageable set that facilitates inference about the status of the Puget Sound ecosystem. Here we suggest that focusing on the specificity and sensitivity of an indicator, in combination with its performance against the “understood by the public and policymakers” criterion introduced above, provides a framework for reporting on the status of Puget Sound.

Previous indicator development efforts in the Puget Sound region (e.g. [34]) and beyond (e.g., [223]) have advocated a two-pronged approach to indicator reporting. Recchia and Whiteman (2009) refer to a coarse-grained evaluation of ecosystem status and trends. This level of indicator reporting is aimed at the general public and policy makers with the goal of providing a limited number of “vital signs” of the ecosystem [223]. Vital Signs may not be very specific, and they do not need to be sensitive on any particular time scale. For instance, abnormalities in blood pressure or temperature indicate some malady, but do not suggest a specific pathology. Likewise, changes in Chinook salmon abundance may be brought about by alterations to water quality, habitat, climatic factors, fishing or numerous other factors, in the marine, freshwater, or terrestrial domains of Puget Sound. Nonetheless, it is likely that changes in Chinook salmon represent a shift in the “health” of the system (Figure 8). As regional managers and scientists consider assembling portfolios of Vital Sign indicators, some indicator criteria may be more important than others. For example, it is clearly crucial that the indicator be understandable to the general public. On the other hand, understanding the variance structure of such indicators may be less critical. By carefully crafting a weighting scheme as described in Section 5.6, it is possible to systematically sift through a large inventory of indicators to generate a short-list of scientifically credible vital sign indicators. Ultimately, the goal of Vital Sign indicators is to provide a limited number of scientifically meaningful, but simple metrics that can generally inform the public and policy makers about the state of the ecosystem.

Figure 8. Indicator species in Puget Sound plotted according to whether they reliably track few (diagnostic) or many (non-specific) Species and Food Web attributes (x-axis) and whether they respond quickly (early warning) or slowly (retrospective) to perturbations. The ranking of indicators as diagnostic vs. non-specific is relative and based on the analysis in [118]. The ranking of indicators as early warning vs. retrospective is also relative, and based on the production to biomass ratios of these seven species. Adapted from [5].



In contrast to Vital Sign indicators, Ecosystem Assessment indicators provide a technically more robust and rigorous understanding of ecosystem structure and function. Assessment indicators provide the detailed information necessary to diagnose specific problems, develop strategies to mitigate these problems, and monitor responses of the ecosystem to management actions on multiple time scales. Thus, Ecosystem Assessment indicators should be diagnostic rather than non-specific, but can span a range of sensitivities, so that a full set includes both early warning and retrospective indicators. The audience for these indicators is scientists and managers who require a detailed understanding of the ecosystem; consequently, criteria related to the technical performance of the indicator should be given increased weight relative to criteria related to salience.

Key Point: Ranking indicators requires careful consideration of the relative importance of evaluation criteria. The importance of the criteria will certainly vary depending on the context within which the indicators are used and the people using them. Thus, ranking requires that managers and scientists work together to weight criteria. Weighting schemes that emphasize communication will inform the selection of Vital Sign indicators, while weightings that stress technical aspects of the data will inform the selection of Ecosystem Assessment Indicators.

Defining Ecosystem Reference Levels: A Case in Puget Sound

1. Ecosystem reference levels: how do we know when EBM has succeeded?

Ocean stewardship is not simple. Rather than maintaining piecemeal efforts, scientists, managers, conservationists, and policymakers have agreed that restoration and protection of the oceans will require a more integrated approach [249-251]. A unified appeal for marine ecosystem-based management (EBM) has made the task of developing concrete methods for implementation quite urgent [20, 252, 253]. Indeed, if the goal is maintenance and sustainable use of a healthy ecosystem [224], it follows that those responsible for achieving this objective require a means to track the progress of their efforts. As discussed above, indicators allow the tracking of progress and change.

Terminology and concepts	
Baseline	Reference level derived from time periods or locations free from human pressures
Benchmark	Indicator value suggestive of progress toward targets
Limit	Reference level pegged to an extreme value beyond which undesired change occurs
Nonlinearity	Sudden change in a response variable resulting from smooth and gradual change in a causal factor
Normative reference level	Reference level defined based on what is socially acceptable, i.e., according to norms
Norms	Define what is generally accepted within a cultural context, and may serve as societal standards to evaluate ecosystem conditions, human activities, or management strategies
Reference direction	Which specifies how the trend in an indicator relates to the desired state of the ecosystem
Reference level	Point value or direction of change used to provide context so that changes in indicator values can be interpreted relative to desired ecosystem states
Reference point	Precise values of indicators used to provide context for the current status of an indicator
Target	Reference level that signals a desired state

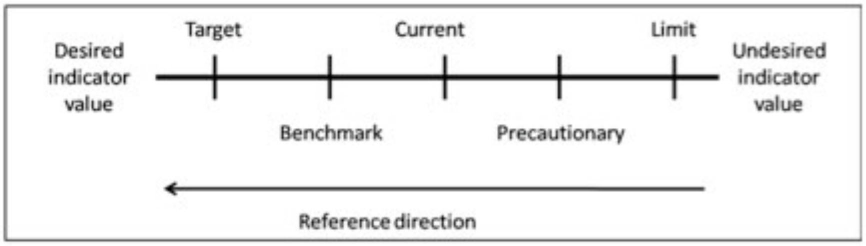
Many authors have considered ecosystem health to be the structure and function of the ecosystem desired by stakeholders in a specific management context [255-258]. Thus, as we have previously emphasized, many attributes of ecosystem health, such as resilience, are difficult to measure directly. Proponents of using human health as an analog to ecosystem health note that just as cholesterol, stress, and income levels can serve as indicators for gauging human health (a state of physical, mental, and social well-being; [225]), the status of an ecosystem's health can be measured via proxy using a suite of ecosystem indicators. For example, it is widely appreciated that the abundances of certain species of jellyfish and top predators provide information about the status of marine ecosystems because they reflect underlying changes in important ecosystem functions (e.g., [226, 227]).

To be useful from a policy and management perspective, ecosystem indicators must be linked to reference levels. Reference levels provide context so that changes in indicator values can be interpreted relative to desired ecosystem states [113, 255, 257, 262]. Following with the human health analogy, one reference level for household income, a social well-being indicator, might be the poverty line [228]. In single-species and single-sector management, reference levels are also fairly well established. Examples include target population sizes for recovery of endangered species [229], the harvest rate corresponding to maximum sustainable yield in a fishery [230], the critical level of nutrient input beyond which a clear freshwater lake becomes turbid [231], and, acceptable concentrations of toxic contaminants in water bodies [232]. While existing reference levels such as these provide a useful starting point [233], EBM requires the consideration of how interactions among species and management sectors affect overall ecosystem state and potential trade-offs among indicator values [234]. Reference levels set to guide management of species, habitats, and water quality individually may need to be modified or supplemented with additional indicators, and corresponding reference levels, in order to steward multiple ecosystem components simultaneously. We believe that many of these challenges can be met by adopting successful approaches from other management contexts for use on the ecosystem level. Here we describe several approaches for linking indicator values and trends to reference levels related to ecosystem health, and provide some examples for how they might be applied in Puget Sound. A summary of existing targets and/or reference levels for Puget Sound follows.

Reference points and reference directions

Reference points are precise values of indicators used to provide context for the current status of an indicator. Establishing a reference point requires substantial understanding of an indicator's properties, but it provides a rigorous way to assess ecosystem status. For some indicators, reference points will have already existed prior to the introduction of EBM. In the case of Puget Sound, the Washington Department of Health provides recommendations regarding human consumption of seafood subject to known levels of toxic contamination [235]. In the short-term, it may be challenging to develop actual point values for ecosystem reference levels [255, 262, 271]. However, a reference direction, which specifies how the trend in an indicator relates to the desired state of the ecosystem, can be informative as well (Figure 9; [236, 237]). In comparison to reference points, the challenge of achieving consensus on reference directions is small and can be applied in data-poor situations [233].

Figure 9. The relationship between target, benchmark, precautionary, and limit reference levels for an ecosystem indicator (adopted from [236]).



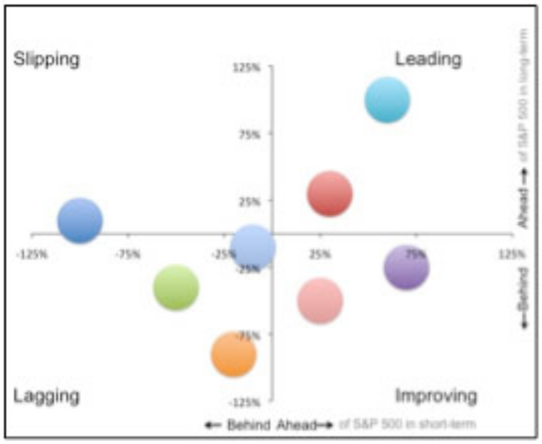
The concept of reference directions is familiar in the context of financial markets. For instance, the Dow Jones Industrial Average is an index representing the performance of 30 large, publicly owned U.S. corporations on the New York Stock Exchange. Though specific reference points are not widely agreed upon [238] it is generally accepted that increases in the Dow Jones are economically favorable and reductions are unfavorable.

A second financial market example illustrates an alternative approach for establishing reference directions, based on relative performance. The S&P 500, a weighted index consisting of 500 companies traded on the New York Stock Exchange, American Stock Exchange, and NASDAQ stock market [239], is commonly used to compare the direction of change of individual companies to the direction of change of the overall financial market ([240]; Figure 10). Companies that show greater percentage increases than the S&P 500 over the short-term (e.g., days, weeks, or months) and long-term (quarters or years) are considered to be leading the market, whereas companies that show lesser percentage increases than the S&P 500 over the short-term and long-term are considered to be lagging the market. Slipping companies are those that are behind the S&P 500 in the short-term but ahead in the long-term, and improving companies are those that are ahead of the S&P 500 in the short-term but behind in the long-term. This approach could be adopted for evaluating ecosystem indicators in Puget Sound relative to a summary index for each PSP goal, and would be useful for distinguishing indicators in need of management attention (lagging, slipping) from those on a desired trajectory (leading, improving).

Reference directions are already used widely in the management of natural systems. For instance, in San Francisco Bay and the North Sea increasing abundance of certain species of jellyfish is viewed as a sign of deteriorating ecosystem health [226], though no exact value corresponding to an undesired abundance level has been established. Similarly, a decline in disturbance-sensitive, specialist seabirds is viewed as indicative of strong anthropogenic influences (e.g., Chesapeake Bay; [241]) or worsening climatic conditions (e.g., central California coast; [242]), but a specific value for the rate or extent of decline marking an undesired state remains ambiguous. As a final example, in 2002 nearly 200 nations pledged to reduce the global rate of biodiversity loss by 2010 without establishing a target level for the amount of reduction that they desired [243].

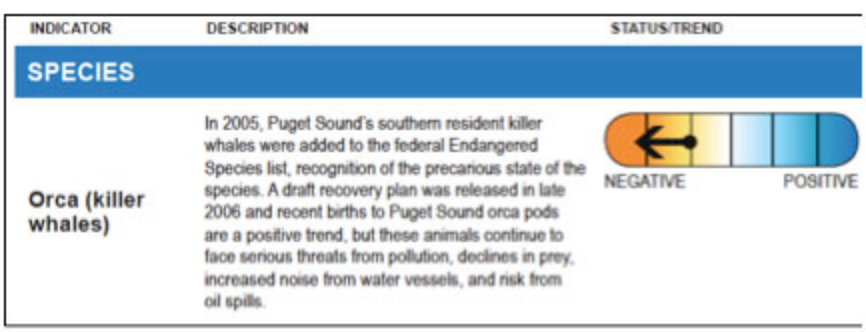
Figure 10. Use of reference directions based on relative performance of individual stocks (circles) and the S&P 500, a weighted index of overall market performance. Stocks that show greater percentage increases than the S&P 500 over the short-term (e.g., days, weeks, or months) and long-term (quarters or years) are considered to be leading the market, whereas stocks that show lesser percentage increases than the S&P 500 over the short-term and long-term are considered to be lagging the market. Slipping stocks are those that are behind the S&P 500 in the short-term

but ahead in the long-term, and improving stocks are those that are ahead of the S&P 500 in the short-term but behind in the long-term. Adapted from www.nytimes.com



In Puget Sound, reference directions for indicators could serve as placeholders in order to allow time for the development of more precise reference points. Indeed, the Puget Sound Action Team (PSAT) has applied the reference direction approach previously [244]. Using a simple and easily-interpreted schematic, PSAT evaluated indicators based on whether their status was generally negative, fair, or positive and whether the trend in the indicator was negative, neutral, positive, or unknown compared to a desired status (Figure 11). In future versions of the PSSU, a similar approach could be applied productively to the indicator assessments presented in Chapters 2 and 3, provided that the direction of change that is considered desirable for each indicator is specified explicitly and its rationale explained.

Figure 11. Example of indicator report card from the 2007 State of the Sound document. This figure shows that the status of one indicator of the health of Puget Sound species, orcas, is generally negative because the dot is to the left of center, and its trend, indicated by the arrow, is also negative. Reproduced from [244].



Target, benchmark, limit, and precautionary reference levels

A construct that has been particularly successful in the realm of fisheries management is the distinction between target and limit reference levels (Figure 9). A target is a reference level that signals a desired state, whereas a limit is a reference level pegged to an extreme value beyond which undesired change occurs [236, 245].

In fisheries and marine EBM limit reference levels thus identify what is to be avoided [20], and can be used to redirect and prioritize management action before irreversible harm occurs. Because of uncertainty inherent to the measurement of any indicator, precautionary or warning reference levels that are more conservative than the limit reference levels may be used (Figure 9; [236, 246]). Target reference levels identify what is to be achieved [20], and in so doing allow managers and policymakers to determine when their efforts and resource allocations have been sufficient [247]. Because indicators respond at varying rates to management actions, target reference levels may be most useful when accompanied by benchmarks, or indicator values suggestive of progress toward targets (Figure 9).

In Puget Sound, the PSP has taken it upon itself to establish targets and benchmarks. Because of legislated restoration and protection deadlines, the PSP has associated a timeline with target and benchmark reference levels. The PSP defines a target as a "desired future numeric value for an ecosystem status indicator in 2020." Similarly, the PSP describes a benchmark as a "measurable interim (i.e., pre-2020) milestone set to demonstrate progress toward a target for an ecosystem status indicator" [76].

Importantly, the indicator associated with a target reference level need not be identical to the indicator associated with the corresponding benchmark. The current financial crisis provides a useful parallel to illustrate this point. The onset of the economic recession in the U.S. was characterized in part by a Gross Domestic Product (GDP) that fell for several months [239]. Thus a target reference level for economic recovery could be measured in terms of a consistent month-to-month rise in GDP. Benchmarks for measuring progress toward this target included a variety of indicators other than GDP, however, such as the number of new unemployment claims filed and new construction permits issued each week [248].

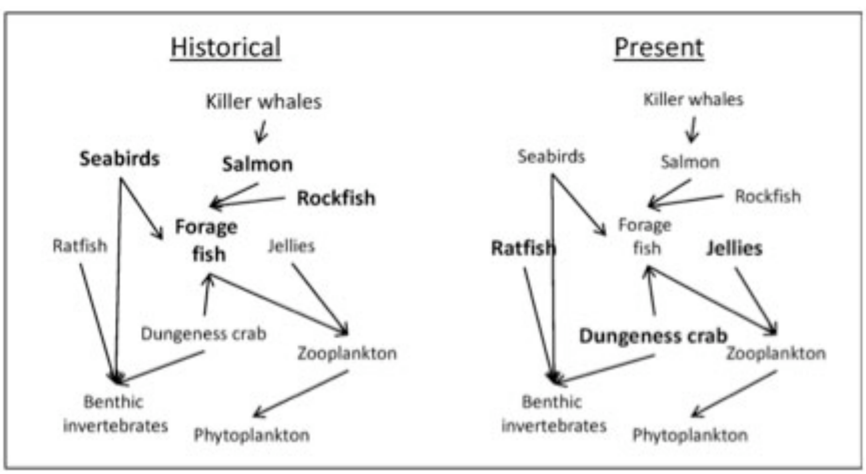
In the context of Puget Sound, a fundamental goal is to achieve a healthy and sustaining population of southern resident killer whales (SRKWs) [1], and one indicator of SRKW population status is the number of individuals in the population. The target reference level associated with the goal of SRKW population recovery may be measured using this indicator, but because the likely response time for achieving the target is several decades, a benchmark might be set using a different indicator, such as a reduced infant mortality rate or an increased annual population growth rate [249].

Because they are a primary interest of the PSP, we focus on approaches for determining target reference levels rather than limits. Though our discussion is framed largely in terms of reference points, we see no reason why targets cannot be defined in terms of reference directions, at least in the short term. However, it is not obvious how to distinguish a benchmark from a target using reference directions alone.

Baseline reference levels

Baseline reference levels are derived from time periods or locations free from human pressures. We use the term baseline inclusive of the structure and function of an ecosystem (1) prior to substantial human impact (i.e., during some 'baseline' time period [250, 251]), (2) inside of areas protected from human impacts [252, 253], and (3) in remote geographic locations subject to minimal human pressures [254]. Recognition of these types of reference levels is crucial for avoiding the shifting baselines syndrome—failing to identify the state of nature absent human impacts so that it is impossible to determine the extent of degradation [251]. As such, there is value in reconstructing time series of both desired and undesired changes in indicators, such as shifts in the abundances of iconic and nuisance species. It can also be quite useful to make comparisons across spatial locations that vary in the extent to which they have been altered by human activities [255]. Even where detailed information is not available, the qualitative difference between present and historic, or disturbed and undisturbed, values of ecosystem indicators can provide a reasonable starting point for determining target reference directions (Figure 12; [256]).

Figure 12. Comparison of a simplified historical and present-day Puget Sound marine food web. Larger, bold font indicates great erabundance/biomass. This figure is intended to be a conceptual schematic, and is not based on historical data. Historical and present-day could be replaced with unexploited and exploited areas or remote and metropolitan locations.



Historical information can be gleaned from a variety of sources, including paleo-ecological records [257] archaeological findings [258], historical documents [259, 260], and long-term ecological data [261, 262]. Additionally, interviews with people who have experience with an ecosystem during different eras of human impact can provide valuable insights into changes in ecosystem indicators over time [263, 264]. Indeed, subjective impressions of how indicators have varied through time can be standardized with known values and used to establish reference levels (e.g., unfished biomass of currently harvested species; [265]). One concern with using historical baselines, however, is that ecosystem dynamics are not necessarily stationary. Climatic shifts and other sources of variation can render historic states unattainable [236]. Such fundamental changes must be appreciated before making the decision to associate an indicator with a target reference level derived from a historical baseline.

Marine protected areas (MPAs) and areas with low human impact provide useful experiments for evaluating the natural biophysical state of an ecosystem absent major, direct anthropogenic influences [41]. Such spatial baseline ecosystems make particularly useful reference levels because they represent one extreme in a spectrum of management possibilities in the contemporary time period. Admittedly, problems exist with these approaches. For instance, geographic variability among reference and impacted sites and anthropogenic activities that manifest effects on regional and even global scales (e.g., climate change) can confound comparisons. Nonetheless, differences between indicators inside and outside of MPAs [266, 267] and near to and far from locations with high human population densities [268-271] can provide a useful basis for calibrating expectations regarding the healthy state of an ecosystem [254, 272, 273].

In Puget Sound, many untapped sources of baseline information exist. For example, archival papers document changes in the abundances of harvested species dating back to at least the 19th century [274]. According to these accounts, species declines appear to have occurred long ago, and quite rapidly: "[f]rom 1869 to 1877 it was not an uncommon occurrence for us to catch from 200 to 300 barrels of herring in a night, but since 1877... the largest night's work is about 20 barrels" [274]. Similarly, historical habitats have been altered drastically: <20% of tidal marshes present in the mid-19th century exist today [275]. Even shorter intervals reveal surprisingly large changes in ecosystem status: current concentrations of polybrominated diphenyl ethers (PBDEs) in southern resident killer whales dwarf the levels detected 10 years earlier [276]. In modern times, spatial differences in the ecological communities within and outside of marine reserves near Edmonds, Hood Canal, and the San Juan Islands suggest the direct negative impacts of fisheries on rockfishes and lingcod [277, 278]. Similarly, comparison of the most populated areas of Puget Sound to more rural areas reveals dramatic differences in the abundance of kelp [272, 279].

In terms of actually setting target and benchmark reference levels using information about baselines, the ultimate decision lies in the hands of policymakers [280]. Following on the example of the change analysis conducted for Puget Sound's tidal marshes, the question remains as to what target reference level is most appropriate given that >80% of the historic habitat has been destroyed since 1850. There is no single and absolutely correct answer to this question. It is up for negotiation among stakeholders, but the knowledge of what existed historically and/or what is currently observed in remote or protected locations provides an idea of what is possible.

Reference levels based on nonlinearities

Nonlinearities are common in nature [281, 282]. Sudden change in ecosystem attributes can result from seemingly smooth and gradual change in physical or biological components [283]. For instance, in kelp forests, increasing sea urchin densities initially produce small or negligible changes in habitat-providing kelp. However, above a threshold sea urchin density, declines in kelp and changes in associated ecological communities can be quite rapid [284, 285]. Similarly, on coral reefs, important ecosystem functions decline rapidly with initial increases in human impacts, but thereafter change quite slowly [254, 286]. These examples illustrate that nonlinearities in functional relationships distinguish environmental conditions or types of management actions leading to smooth and proportional changes in ecosystem state from those that cause abrupt and disproportionately large changes. An understanding of nonlinearities is highly relevant in the context of managing the Puget Sound ecosystem because it presents opportunities to define clear and objective reference points [287, 288].

Nonlinear functional relationships underpin commonly-used management reference points in fisheries and in the control of contaminants in the environment (e.g., chemicals, effluents, non-native species, etc.). For instance, the spawning stock biomass and the fishing mortality rate corresponding to maximum sustainable yield are two of many biological reference points used in single-species fisheries management [289]. The concept of maximum sustainable yield is based on the expectation that the yield from the fishery peaks at intermediate levels of population biomass and fishing mortality rate imposed on the target population. These nonlinear relationships are the consequence of assumptions in surplus production models of fish population dynamics, and make it possible to identify objectively a reference point on either side of which fishing yield is reduced. In ecotoxicology, contaminants frequently have little or no deleterious effects on biota below some minimum concentration but lead to serious sublethal or lethal effects thereafter (Figure 13 a,b). Thus, a reference point can be defined based on a threshold in such exposure-response relationships [232]. In both situations, the reference points are linked mathematically to a functional relationship of interest to managers and policymakers [246]. The functional relationships most relevant in a marine EBM context fall into two broad categories [281]. In both cases, the response variables of interest are ecosystem attributes that influence ecosystem health, and might include nutrient cycling, energetic rates, and resilience. These are akin to the toxin concentrations in ecotoxicological studies. In the first category, the predictor variable (analogous to the exposure effect in ecotoxicological studies) is some environmental condition(s). For example, reductions in the amount of upwelling along the west coast of the United States are associated with an exponential increase in seabird mortality events, which appear to be indicative of broader changes in ecosystem attributes, such as productivity [242]. In the second category, the predictor variable is a factor(s) under the control of managers and policymakers. For instance, a marine food web model for northern British Columbia suggests that several ecosystem attributes show nonlinear declines with increasing fishing pressure and with reductions in nearshore habitat quantity and quality [288]. In both cases, it is possible to define mathematically a point separating rapid and dramatic changes in the ecosystem attributes from more smooth and gradual changes (Figure 13c,d).

Reference levels for ecosystem indicators can be derived from either category of nonlinearity. The guidelines for selecting a reference point based on a functional relationship between predictable environmental conditions or factors under the control of managers and policymakers and ecosystem attributes are as follows:

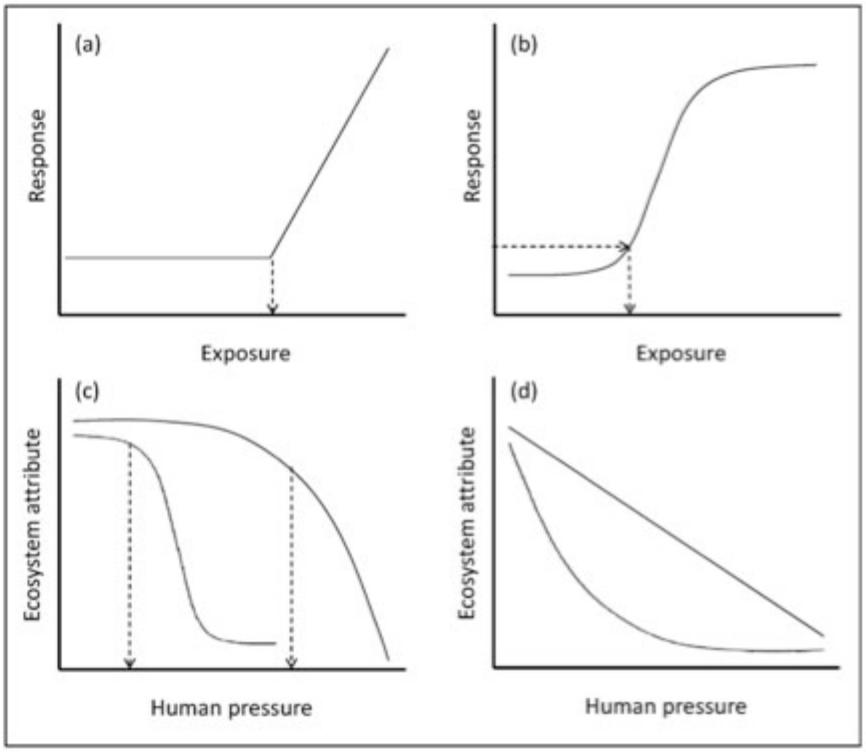
1. Examine the functional relationship of interest, using data, models, or both;
2. Use information theoretic techniques [290] to fit alternative linear and nonlinear mathematical functions to the relationship;
3. If the best-fit function is nonlinear, select a reference point that distinguishes the steep from the shallow portion of the curve [288].

Reasonable target reference levels for the sigmoidal and concave functional relationships shown in Figure 13c would correspond to portions of the curves where the value of the ecosystem attribute is high and the rate of change in the ecosystem attribute with increasing human pressure is low, i.e., where the dashed arrows intersect the curves.

The identification of nonlinear relationships between pressures and ecosystem attributes could be used productively to set target reference levels in Puget Sound. One way to detect nonlinearities relevant for food web health in particular would harness the power of a recently developed Ecopath model for the Central Basin of Puget Sound [26]. Indeed, Samhouri et al. (2010) recently followed the methods outlined in steps 1-3 above to determine food web reference levels associated with two different stressors (fishing and habitat modification) along the British Columbia coast [288]. Empirical examples of nonlinearities already exist as well. For instance, Rice (2007) found that there was a drastic and abrupt decline in the abundance of diving ducks and herons in Puget Sound above ~70% alongshore urban land cover [291]. Given the potential for these species to act as reliable indicators of ecosystem health [45, 118], a target reference level for their abundance based on the effects of urbanization may be sensible.

A concerted effort to gather information about functional relationships between ecosystem indicators and pressures would greatly advance efforts to set target and benchmark reference levels in Puget Sound. These reference points should be considered complementary to those based on baseline conditions.

Figure 13. Examples of nonlinear relationships in ecotoxicological (a-b) and ecosystem (c-d) studies. (a) A hockey stick relationship in which the reference point could be either the LOEC (lowest observed effect concentration), i.e., the lowest concentration causing an effect that is statistically different from control (upper 95% CI of x-axis threshold estimate), or a NOEC (no observed effect concentration), i.e., the highest concentration below LOEC (could be lower 95% CI of x-axis threshold estimate). (b) A sigmoidal relationship in which the reference point is an Ecp, the concentration causing the effect in proportion p of the population (e.g., LC50). (c) It is possible to identify objectively a reference point in terms of human pressure if the relationship between the predictor variable and the ecosystem attribute is sigmoidal or concave. (d) A convex relationship suggests that management actions that reduce human pressures to steeper portions of the function will produce the greatest improvements in the ecosystem attribute. Linear functions do not allow the objective identification of a threshold-based reference point. In all figures, dashed arrows indicate possible reference points. In (c) and (d), positive values on the y-axis are assumed to represent the desired state of the ecosystem attribute.



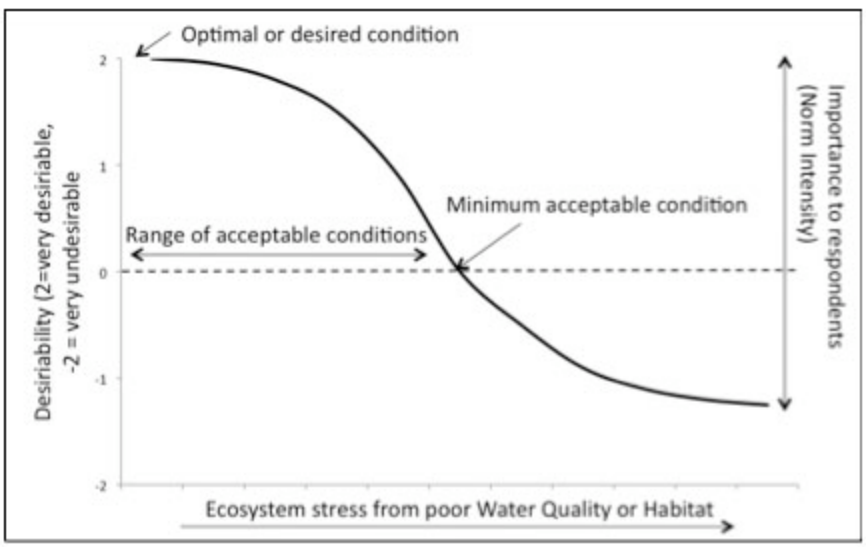
Normative reference levels

In the PSP parlance, a target is defined as a desired state [37]. Consequently, the process of establishing desirability must comprise not just ecological understanding, but also societal values [280, 292]. A powerful way to collect and organize data about societal values is the normative approach [293]. Norms define what is generally accepted within a cultural context, and may serve as societal standards to evaluate ecosystem conditions, human activities, or management strategies.

Norms are typically described by means of a graphic device referred to as a social norm curve (Figure 14; [294]). In applying this concept to ecosystem targets, the x-axis represents environmental stressors and the y-axis portrays stakeholder survey responses. Thus, social norm curves might represent the results from structured surveys in which respondents are asked about the acceptability of different ecosystem states, which vary with changes in pressures like water quality or habitat modification. The goal of stakeholder surveys is to identify the acceptability of alternative ecosystem scenarios that illustrate trade-offs among different aspects of ecosystem health (e.g., food web health, water quality, habitat, key species, and human well-being). Alternative scenarios can be portrayed using easily-interpreted, stylized artistic renderings of the ecosystem under consideration that highlight key trade-offs among different ecosystem components [295, 296]. Targets and benchmarks can be set based on scenarios that are deemed minimally acceptable by the average respondent, subject to legal, regulatory or other constraints. A key challenge with this approach is dealing with the fact ecosystem conditions are rarely produced by one individual's behavior but by the cumulative effects of many people's behavior.

In Puget Sound, the PSP and the World Resources Institute have already initiated the process of soliciting feedback from stakeholders about how they define a healthy Puget Sound [297]. This work could be built upon by extending social norms surveys to Native American tribes and stakeholder groups (e.g., commercial fishers, recreational fishers, agricultural interests, builders and developers, members of environmental organizations, coastal homeowners, etc.). In other marine systems around the world, similar surveys have been conducted by soliciting formal feedback about reference levels from regional scientists [298]. By establishing ranges of acceptability, the PSP can ensure that its targets are in sync with the desires of the public which they are meant to serve. Thus rigorously conducted normative surveys provide a tool to inform target selection within the realm of what is ecologically and legally possible and appropriate.

Figure 14. Hypothetical social norm curve. The x-axis shows increasing ecosystem stress from poor water quality or habitat, and the y-axis portrays stakeholder values regarding the desirability of different ecosystem states. Y-axis values >0 reflect socially acceptable ecosystem states, and the range of responses reflects the importance of ecosystem status to stakeholders.



Focus for the future: targets and success in Puget Sound

A catalog of ecosystem indicators is only useful in the extent to which it informs answers to the question "Is Puget Sound healthy?" In economics, it is not meaningful to report on the rate at which unemployment claims are filed unless it is known that an increase in that rate indicates a decline in the business cycle [248]. Similarly, in the absence of reference levels, a list of values for indicators alone provides no insight into the status of the ecosystem relative to its desired state. Thus, establishing a target associated with each indicator is fundamental to the success of the Puget Sound Partnership's ecosystem-based management efforts, for several reasons.

First, the articulation of targets associated with each indicator allows for a careful accounting of management successes and failures. Targets remove ambiguity from well-intended but vague policy goals and facilitate the development of a roadmap for new actions, policies, and management strategy evaluations. Pathways of ecosystem degradation may involve sequential losses of structural features (relative abundance of species), species, and functional components (all species responsible for particular ecological processes) [299]. Awareness of this type of progression can provide justification for benchmark reference levels that track recovery along similar pathways (but in reverse) toward more ambitious, longer-term targets.

Second, as described in the Futures section above, creating targets for individual indicators brings into focus the notion of trade-offs. For instance, interactions among species, such as harbor seals and forage fishes, may render obsolete target reference levels instituted for each group individually because some combinations of abundance are ecologically impossible. Likewise, establishing targets for contaminant loads related to water quality may interact with desired states of human well-being. The use of conceptual and quantitative ecosystem models and other tools can help to reveal the spectrum of possible combinations of target reference levels for multiple indicators simultaneously.

Third, target reference levels can also be viewed as the antecedent of legal statutes and regulations. In other words, the formal establishment of targets sets up a system of EBM accountability. These reference levels can be used as a springboard for enacting and enforcing policies to ensure that human activities do not exceed levels that would prevent the achievement of ecosystem recovery goals [300].

Fourth, targets can serve a useful role if they are linked to decision criteria or control rules [246, 287]. In other words, it would serve the PSP's interests if target values for indicators were associated with management responses. For instance, in the case of Chinook salmon in Puget Sound, achievement of the near-term recovery target of 1,600 spawners [15] might be linked to a control rule that influenced efforts to restore riparian vegetation and increase woody debris. Such built-in linkages would contribute to the efficient allocation of PSP financial resources and solidify a clear plan for active and adaptive management.

We have not yet attempted an exhaustive review of targets for each indicator evaluated in Section 4. A summary of existing targets specific to Puget Sound follows. For those indicators where targets or reference levels do not exist, it should be possible to determine appropriate targets using any of the three approaches outlined in Sections 5.5-5.7. Initially, it should suffice to define a reference direction for each indicator used to evaluate ecosystem status by identifying baselines, recognizing nonlinearities, or assessing social norms. Eventually, however, the PSP should strive to produce target reference points wherever possible. Key point: To be useful from a policy and management perspective, ecosystem indicators must be linked to reference levels. Reference levels provide context so that changes in indicator values can be interpreted relative to desired ecosystem states. Establishing targets for individual indicators brings into focus the notion of trade-offs among competing ecosystem services. The use of conceptual and quantitative ecosystem models can reveal the spectrum of possible combinations of target reference levels for multiple indicators simultaneously.

Existing Targets for Puget Sound

This section provides a brief summary of existing targets for Puget Sound including those for species, habitats, water quality, and water quantity.

Existing Species Targets

In Puget Sound, target reference levels have been assigned to a subset of ecosystem indicators. For indicators meant to inform the PSP Species Goal, it is worth noting that targets have been established primarily for species that have been listed as vulnerable, threatened, endangered, etc. at the state or federal level (especially marine mammals). Consequently, these targets frequently represent minimum requirements because many of the species were or are currently recovering from depressed states. Once achieved, such targets should be considered limit reference levels under the vocabulary introduced in this Section, and new targets should be established. Table 30 presents a selection of Species indicators that clearly met the “Linkable to scientifically-defined reference points and progress targets” criterion and for which targets have been defined in Puget Sound or Washington State specifically.

Existing Habitat Targets

We identified targets for two indicators meant to inform the PSP Habitats Goal: riparian habitat and aggregation/deposition zones (Table 31). For riparian habitats, we report targets for indicators intended to represent important ecosystem functions such as sediment, nutrient, and pollutant removal, erosion control, recruitment of large woody debris, regulated water temperature, availability of habitat for wildlife, and diversity of microclimates. For aggregation/deposition zones, we report a target that would ensure the maintenance of the structure and function of this habitat type in its current form.

Existing Water Quality Targets

The State of Washington has developed several sets of standards and criteria for both freshwater and marine surface water quality. Standards for physical and chemical parameters are generally established based on habitat type or water use category. For freshwater the Aquatic Life Use categories are summarized in Table 32; the Recreational Use categories are summarized in Table 36 [130, 138]. Water use designations for individual rivers and streams are listed by Water Resource Inventory Area (WRIA) in WAC 173-201A-602. The Aquatic Life Use categories for marine waters are summarized in Table 33. The majority of Puget Sound is listed as Extraordinary quality with the exception of designated bays and inlets (e.g. Elliot Bay, South Puget Sound, and Possession Sound) which are listed as either Excellent or Good. The sole area with a Poor designation is a potion of Commencement Bay, south and east of south 11th Street [301].

Summaries of the water quality criteria for physical and chemical properties in freshwater and marine water are presented in Table 32 and Table 33, respectively. Nutrient action levels for lakes are listed in Table 34. Surface water quality criteria for freshwater and marine waters for trace organic and inorganic chemicals is shown in Table 35; additional criteria for the protection of human health are included in Chapter 40 of the Code of Federal Regulations [302]. Water quality criteria for bacteria, which are meant to be protective of human health, are listed in Table 36.

Existing Water Quantity Targets

There are three indicators of Freshwater Water Quantity with established goals or targets (Table 37). Instream flow rule establish minimum flow requirements on several rivers and streams in the Puget Sound region. The flow rules are meant to legally acknowledge ecological flow requirements. A detailed review of the actual flow regimes versus the instream flow rules is presented in Chapter 2 of the PSSU.

There are also targets for flooding that are established at each gauge station. While not strictly goals, these can be used to monitor the potentially effects of land use change or climate change on flooding. Finally the State of Washington has established efficiency requirements through the Municipal Water Law. While this does not strictly define conservation targets it does mandate system loss limited and the establishment of efficiency programs within each supply system.

Tables - Defining ecosystem reference levels

Table 30. Species indicators for which targets have been established in Puget Sound and/or Washington state.

Species indicator	Target	Achieved	Reference
Bald eagle	Equilibrium population abundance is ~6,000 individuals in WA state	Yes	[303]
Harbor seal	Carrying capacity of 10,000-13,000 individuals (WA inland waters)	Yes	[304]
Peregrine falcon	Delisting criteria: 30 reproductive pairs in WA state; 1.5 young/territorial pair per year for a 5-year period	Yes	[305]
Pinto abalone	Achieve >0.15 individuals m^{-2} to avoid Allee effects due to reproductive failure	No	[117]
Southern Resident killer whale	Delisting criteria: Sustained average population growth of 2.3% per year for 28 yrs	No	[249]

Table 31. Habitat indicators for which targets have been established in Puget Sound and/or Washington state.

Habitat indicator	Target	Reference
Riparian habitat		
% of riparian habitat with a lateral extent >30 m	70-80%	[306]
% of riparian habitat with a lateral extent >100 m	40-50%	[306]
% of riparian habitat with a lateral extent <10m (encroachment)	10-20%	[306]
Corridor continuity (road crossings/km)	1-2	[306]
% natural forest or wetland cover	75-90%	[306]
% mature native vegetation or wetland	75-90%	[306]
Buffer width for 75% effective nitrogen removal	25m	[307]
Aggregation/deposition zones		
Deposition rate	>0.32 cm yr^{-1}	[328-331]

Table 32. Freshwater water quality criteria per Washington Administrative Code based on aquatic life use

Parameter	Categories for Freshwater Aquatic Life								Ref.	Notes
	River - Char Spawning and Rearing	River - Core Summer Salmonid Habitat	River - Salmonid Spawning, Rearing, and	River - Salmonid Rearing and Migration Only	River - Non-anadromous Interior Redband Trout	River - Indigenous Warm Water Species	River - Other	Lakes		
Dissolved Oxygen (Lowest 1-Day Min.)	9.5 mg/L	9.5 mg/L	8.0 mg/L	6.5 mg/L	8.0 mg/L	6.5 mg/L	Not less than 0.2 mg/L below natural conditions.		[92, 130]	
Temperature 7-day average of the daily max. temp. (7-DADMax)	12°C (53.6°F)	16°C (60.8°F)	17.5°C (63.5°F)	17.5°C (63.5°F)	18°C (64.4°F)	20°C (68°F)	Not more than 0.3°C above natural conditions.		[93, 130, 308]	a)
pH	6.5 - 8.5, human-caused variation less than 0.2 units		6.5 - 8.5; human-caused variation less than 0.5 units						[130]	b)
Total Dissolved Gas	Less than 110 % of saturation								[130]	
Turbidity	5 NTU increase when the background is 50 NTU or less; or A 10% increase when the background is 50 NTU or more.			10 NTU (<50 NTU); 20% inc. (>50 NTU)	5 NTU (<50 NTU); 10% inc. (>50 NTU)	10 NTU (<50 NTU); 20% inc. (>50 NTU)			[130]	

Notes: a) Special protection per Ecology publication 06-10-038. 7-DADMax = 9°C (48.2°F) at the initiation of spawning and at fry emergence for char. 7-DADMax = 13°C (55.4°F) at the initiation of spawning for salmon and at fry emergence for salmon and trout.
b) See [309] for a non-compliance analysis

Table 33 - Marine water quality criteria per Washington Administrative Code based on aquatic life use.

Parameter	Categories for Marine Water Aquatic Life					Ref.	Notes
	Extraordinary quality	Excellent quality	Good quality	Fair quality	Other		
Dissolved Oxygen (Lowest 1-Day Min.)	7.0 mg/L	6.0 mg/L	5.0 mg/L	4.0 mg/L	Not less than 0.2 mg/L: below natural conditions	[92, 131]	
Temperature (1-day max.)	13°C (55.4°F)	16°C (60.8°F)	19°C (66.2°F)	22°C (71.6°F)	Not more than 0.3°C above natural conditions	[93, 131]	a)
pH	7-8.5; human-caused var. <0.2 units	7-8.5; human-caused var. <0.5 units		6.5-9.0; human-caused var. <0.5 units		[131]	
Total Dissolved Gas							
Turbidity	• 5 NTU increase when background is 50 NTU or less; or • A 10% increase in when the background is 50 NTU or more.		• 10 NTU increase when background is 50 NTU or less; or • A 20% increase in when the background is 50 NTU or more.				
Notes: a) Criteria for Other marine water is based on 7-day average of maximum daily temperature (7-DADMax)							

Table 34. Nutrient action levels for lakes in the Puget Sound ecoregion. If epilimnetic TP values exceed action levels a lake-specific study should be implemented per WAC 173-201A-230 (2).

Trophic State	Ambient Total Phosphorus (μg/l)	Criteria	Ref.
Ultra-oligotrophic	0-4	<4	[136, 308]
Oligotrophic	4-10	<10	[136, 308]
Lower mesotrophic	10-20	<20	[136, 308]
Action Value	>20		[136, 308]

Table 35. Water quality criteria for toxic substances for the protection of aquatic life. For human health standards see 40CFR Ch.1 (7–1–06 Edition) 131.36. References: [302, 310]

	Freshwater		Marine Water	
Substance	**Acute[a]**	**Chronic[b]**	**Acute[a]**	**Chronic[b]**
Aldrin/Dieldrin[e]	2.5	0.0019	0.71	0.0019
Ammonia	f,c	g,d	0.233[h,c]	0.035[h,d]
(unionized NH_3)[hh]	g	g		
Arsenic[dd]	360.0[c]	190.0[d]	69.0[c,ll]	36.0[d,cc,ll]
Cadmium[dd]	i,c	j,d	42.0[c]	9.3[d]
Chlordane	2.4	0.0043	0.09	0.004
Chloride (Dissolved)[k]	860.0[h,c]	230.0[h,d]	-	-
Chlorine (Total Residual)	19.0[c]	11.0[d]	13.0[c]	7.5[d]
Chlorpyrifos	0.083[c]	0.041[d]	0.011[c]	0.0056[d]
Chromium (Hex)[dd]	15.0[c,l,ii]	10.0[d,jj]	1,100.0[c,l,ll]	50.0[d,ll]
Chromium (Tri)[gg]	m,c	n,d	-	-
Copper[dd]	o,c	p,d	4.8[c,ll]	3.1[d,ll]
Cyanide[ee]	22.0[c]	5.2[d]	1.0[c,mm]	d,mm
DDT (and metabolites)	1.1	0.001	0.13	0.001
Dieldrin/Aldrin[e]	2.5	0.0019	0.71	0.0019
Endosulfan	0.22	0.056	0.034	0.0087
Endrin	0.18	0.0023	0.037	0.0023
Heptachlor	0.52	0.0038	0.053	0.0036
Hexachlorocyclohexane (Lindane)	2.0	0.08	0.16	-
Lead[dd]	q,c	r,d	210.0[c,ll]	8.1[d,ll]
Mercury[s]	2.1[c,kk,dd]	0.012[d,ff]	1.8[c,ll,dd]	0.025[d,ff]
Nickel[dd]	t,c	u,d	74.0[c,ll]	8.2[d,ll]
Parathion	0.065[c]	0.013[d]	-	-
Pentachlorophenol (PCP)	w,c	v,d	13.0[c]	7.9[d]
Polychlorinated				
Biphenyls (PCBs)	2.0	0.014	10.0	0.030
Selenium	20.0[c,ff]	5.0[d,ff]	290[c,ll,dd]	71.0[d,x,ll,dd]
Silver[dd]	y	-	1.9[ll]	-
Toxaphene	0.73[c,z]	0.0002[d]	0.21[c,z]	0.0002[d]
Zinc[dd]	aa,c	bb,d	90.0[c,ll]	81.0[d,ll]

NOTES:	
a.	An instantaneous concentration not to be exceeded.
b.	A 24-hour average not to be exceeded.
c.	A 1-hour average concentration not to be exceeded more than once every three years on the average.
d.	A 4-day average concentration not to be exceeded more than once every three years on the average.
e.	Sum of the Aldrin and Dieldrin concentrations.
f.	Shall not exceed the numerical value in total ammonia (mg N/L) given by:

For salmonids present:	$\frac{0.275}{1 + 10^{7.204-pH}}$	+	$\frac{39.0}{1 + 10^{pH-7.204}}$
For salmonids absent:	$\frac{0.411}{1 + 10^{7.204-pH}}$	+	$\frac{58.4}{1 + 10^{pH-7.204}}$

g.	Shall not exceed the numerical concentration calculated as follows:
	Unionized ammonia concentration for waters where salmonid habitat is an existing or designated use:

$0.80 \div (FT)(FPH)(RATIO)$			
where:	FT	=	1.4; for $15 \le T \le 30$
	FT	=	$10^{[0.03(20-T)]}$; for $0 \le T \le 15$
	FPH	=	1; for $8 \le pH \le 9$
	FPH	=	$(1 + 10^{(7.4-pH)}) \div 1.25$; for $6.5 \le pH \le 8.0$
	RATIO	=	13.5; for $7.7 \le pH \le 9$
	RATIO	=	$(20.25 \times 10^{(7.7-pH)}) \div (1 + 10^{(7.4-pH)})$; for $6.5 \le pH \le 7.7$

Total ammonia concentrations for waters where salmonid habitat is not an existing or designated use and other fish early life stages are absent:

where: A = the greater of either T (°C) or 7.

Applied as a thirty-day average concentration of total ammonia nitrogen (in mg N/L) not to be exceeded more than once every three years on average. The highest four-day average within the thirty-day period should not exceed 2.5 times the chronic criterion.

Total ammonia concentration for waters where salmonid habitat is not an existing or designated use and other fish early life stages are present:

where: B = the lower of either 2.85, or $1.45 \times 10^{0.028 \times (25-T)}$. T = temperature °C.

Applied as a thirty-day average concentration of total ammonia nitrogen (in mg N/L) not to be exceeded more than once every three years on the average. The highest four-day average within the thirty-day period should not exceed 2.5 times the chronic criterion.

h.	Measured in mg/L.
i.	≤ (0.944)(e(1.128[ln(hardness)]-3.828)) at hardness = 100. Conversion factor (CF) of 0.944 is hardness dependent. CF is calculated for other hardnesses as follows: CF = 1.136672 - [(ln hardness)(0.041838)].
j.	≤ (0.909)(e(0.7852[ln(hardness)]-3.490)) at hardness = 100. Conversions factor (CF) of 0.909 is hardness dependent. CF is calculated for other hardnesses as follows: CF = 1.101672 - [(ln hardness)(0.041838)].
k.	Criterion based on dissolved chloride in association with sodium. This criterion probably will not be adequately protective when the chloride is associated with potassium, calcium, or magnesium, rather than sodium.
l.	Salinity dependent effects. At low salinity the 1-hour average may not be sufficiently protective.
m.	$\le (0.316)e^{(0.8190[\ln(hardness)] + 3.688)}$
n.	$\le (0.860)e^{(0.8190[\ln(hardness)] + 1.561)}$
o.	$\le (0.960)(e^{(0.9422[\ln(hardness)] - 1.464)})$
p.	$\le (0.960)(e^{(0.8545[\ln(hardness)] - 1.465)})$
q.	$\le (0.791)(e^{(1.273[\ln(hardness)] - 1.460)})$ at hardness = 100. Conversion factor (CF) of 0.791 is hardness dependent. CF is calculated for other hardnesses as follows: CF = 1.46203 - [(ln hardness)(0.145712)].
r.	$\le (0.791)(e^{(1.273[\ln(hardness)] - 4.705)})$ at hardness = 100. Conversion factor (CF) of 0.791 is hardness dependent. CF is calculated for other hardnesses as follows: CF = 1.46203 - [(ln hardness)(0.145712)].
s.	If the four-day average chronic concentration is exceeded more than once in a three-year period, the edible portion of the consumed species should be analyzed. Said edible tissue concentrations shall not be allowed to exceed 1.0 mg/kg of methylmercury.
t.	$\le (0.998)(e^{(0.8460[\ln(hardness)] + 3.3612)})$
u.	$\le (0.997)(e^{(0.8460[\ln(hardness)] + 1.1645)})$
v.	$\le e^{[1.005(pH) - 5.290]}$
w.	$\le e^{[1.005(pH) - 4.830]}$
x.	The status of the fish community should be monitored whenever the concentration of selenium exceeds 5.0 ug/ l in salt water.
y.	$\le (0.85)(e^{(1.72[\ln(hardness)] - 6.52)})$
z.	Channel Catfish may be more acutely sensitive.
aa.	$\le (0.978)(e^{(0.8473[\ln(hardness)] + 0.8604)})$
bb.	$\le (0.986)(e^{(0.8473[\ln(hardness)] + 0.7614)})$
cc.	Nonlethal effects (growth, C-14 uptake, and chlorophyll production) to diatoms (*Thalassiosira aestivalis* and *Skeletonema costatum*) which are common to Washington's waters have been noted at levels below the established criteria. The importance of these effects to the diatom populations and the aquatic system is sufficiently in question to persuade the state to adopt the USEPA National Criteria value (36 µg/L) as the state threshold criteria, however, wherever practical the ambient concentrations should not be allowed to exceed a chronic marine concentration of 21 µg/L.
dd.	These ambient criteria in the table are for the dissolved fraction. The cyanide criteria are based on the weak acid dissociable method. The metals criteria may not be used to calculate total

Table 36. Bacteria water quality standards for Freshwater and Marine Water by water use category as defined by the Washington Administrative Code.

Parameter	Water Use Category				
	Extraordinary Primary Contact Recreation	**Primary Contact Recreation**	**Secondary Contact Recreation**	**Shellfish Harvest**	**Ref.**
Freshwater					
Fecal Coliform (geometric mean)	50 col./100 mL	100 col./100 mL	200 col./100 mL		[130]
Fecal Coliform (maximum)	100 col./100 mL	200 col./100 mL	400 col./100mL		[130]
Marine Water					
Fecal Coliform (geometric mean)		14 col./100 mL	70 col./100 mL	14 col./100 mL	[131]
Fecal Coliform (maximum)		43 col./100 mL	208 col./100 mL	43 col./100 mL	[131]

Table 37. Water Quantity indicators for which targets have been established in Puget Sound and/or Washington state.

Water Quantity indicator	Target	Achieved	Reference
Instream Flow Rules	Instream flow rules have been established for several streams and rivers in the Puget Sound watershed.	No[1]	[311-313]
Flood Stage	River Flood Stage	No	[314]
Per Capita Water Use	Municipal Water Law requires efficiency programs for suppliers	Yes	[315]
Notes - see PSSU Chapter 2a, Status and Trends of Violations of Instream Flow Rules			

Glossary

Attribute	characteristic that is of scientific and/or management importance, but insufficiently specific and/or logistically challenging to measure directly; also, ecological characteristic that specifically describes the state of Focal Components
Baseline	reference level derived from time periods or locations free from human pressures
Benchmark	indicator value suggestive of progress toward targets
CCME	Canadian Council of Ministers of the Environment
CFR	Code of Federal Regulations
Criteria	standards against which indicators were evaluated
Data considerations	indicator evaluation criteria related to the actual measurement of the indicator
DO	Dissolved Oxygen
Domain	distinct ecological areas that contain unique qualities or traits; terrestrial, freshwater, marine, interface/ecotone
Driver	factor that result in pressures that cause changes in the system
Driver-Pressure-State-Impact-Response (DPSIR)	conceptual framework that has been broadly applied in terrestrial and aquatic environmental assessments
EBM	Ecosystem Based Management
Ecosystem assessment indicator	technically robust and rigorous metric used by scientists and managers to understand of ecosystem structure and function
EPM	Ecosystem Portfolio Model
ESA	Endangered Species Act
Focal component	the major ecological characteristics of an ecosystem that capture the relevant scientific information in a limited number of discrete, but not necessarily independent categories
FRAP	Future Risk Assessment Project
GDP	Gross Domestic Product
GIS	Geographical Information System
Impact	measures of the effect of change in state variables such as loss of biodiversity, declines in productivity and yield, etc
Improving indicator	indicator that is increasing faster in the short-term but slower in the long-term than an index that captures aggregate changes in multiple indicators
IBI	Index of Biologic Integrity

Indicator	quantitative biological, chemical, physical, social, or economic measurements that serve as proxies for difficult-to-measure attributes of natural and socio-economic systems
JISAO	Joint Institute for the Study of the Atmosphere and Ocean
Lagging indicator	indicator that is increasing slower in the short- and long-term than an index that captures aggregate changes in multiple indicators
Leading indicator	indicator that is increasing faster in the short- and long-term than an index that captures aggregate changes in multiple indicators
Limit	reference level pegged to an extreme value beyond which undesired change occurs
Management strategy evaluation (MSE)	conceptual framework that enables the testing and comparison of different management strategies designed to achieve specified management goals
MPA	Marine protected areas
NMFS	NOAA National Martine Fisheries Service
Nonlinearity	sudden change in a response variable resulting from smooth and gradual change in a causal factor
Normative reference level	reference level defined based on what is socially acceptable, i.e., according to norms
Norms	define what is generally accepted within a cultural context, and may serve as societal standards to evaluate ecosystem conditions, human activities, or management strategies
Open Standards	Open Standards for the Practice of Conservation, developed by the Conservation Measures Partnership, Version 2.0 released in 2007. Available at http://www.conservationmeasures.org/initiatives/standards-for-project-management. The Open Standards are a series of five steps that comprise the project management cycle, with the aim of providing a framework and guidance for successful conservation action. They define conservation efforts as "projects," and bring together common concepts, approaches, and terminology in conservation project design, management and monitoring. For more information, see [3].
Other considerations	indicator evaluation criteria that make an indicator useful, but without which an indicator remains scientifically informative
PAH	polycyclic aromatic hydrocarbons
PBT	Persistent Bioaccumulative Toxics
PCB	polychlorinated biphenyls
PDBE	polybrominated diphenyl ethers
Performance Management	A system to track implementation and communicate progress of a conservation project or program

Precautionary reference level	reference level pegged to an extreme value beyond which undesired change occurs, but set to be more conservative than the limit; a.k.a. warning reference level
Pressure	factor that cause changes in state or condition. They can be mapped to specific drivers
Primary considerations	essential indicator evaluation criteria that should be fulfilled by an indicator in order for it to provide scientifically useful information about the status of the ecosystem in relation to PSP goals
PSAT	Puget Sound Action Team
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
PSP	Puget Sound Partnership
PSP Goals	combine societal values and scientific understanding to define a desired ecosystem condition, and include: Human health, Human well-being, Species and Food Webs, Habitats, Water Quantity, Water Quality
PSSU	Puget Sound Science Update
Ranking scheme	approach used to weight indicator evaluation criteria
Reference direction	which specifies how the trend in an indicator relates to the desired state of the ecosystem
Reference level	Point value or direction of change used to provide context so that changes in indicator values can be interpreted relative to desired ecosystem states
Reference point	Precise values of indicators used to provide context for the current status of an indicator
Response	Actions (regulatory and otherwise) that are taken in response to predicted impacts
Results chains	Map specific management strategies to their expected outcome (e.g., reduction of a threat) and their impact on key components of the ecosystem. One component in the Open Standards framework being used by the PSP to guide its performance management strategy. Results chains are diagrams that show how a particular action taken will lead to some desired result, by linking short-, medium- and long-term results in "if...then" statements. Comprised of three basic elements: strategy, expected outcomes, and desired impacts. Developed for use as part of the Puget Sound Partnership's Performance Management System in {Neuman, 2009 #20}.
Slipping indicator	Indicator that is increasing faster in the long-term but slower in the short-term than an index that captures aggregate changes in multiple indicators
SMA	Shoreline Management Act
SRKW	southern resident killer whales
State	Condition of the ecosystem (including physical, chemical, and biotic factors)
Target	Reference level that signals a desired state
Threats	Any activities that have altered the ecosystem in the past or present, or are

	likely to in the future
UERL	Urban Ecology Research Lab
USFWS	U.S. Fish and Wildlife Service
Vital sign indicator	Scientifically meaningful, but simple, metric that can generally inform the public and policy makers about the state of the ecosystem
WAC	Washington Administrative Code
WDFW	Washington Department of Fish and Wildlife
WDNR	Washington Department of Natural Resources
WDOE	Washington Department of Ecology
WDOH	Washington Department of Health
WQI	Water Quality Index

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Indicator Evaluation Spreadsheets

1. Species, Food Web and Habitat Indicator Evaluations:

Species, Food Webs and Habitat Spreadsheet

Species, Food Webs and Habitats Literature Cited

Water Quality and Quantity Indicator Evaluations:

Water Quality and Quantity Spreadsheet

Water Quality Literature Cited

Water Quantity Literature Cited